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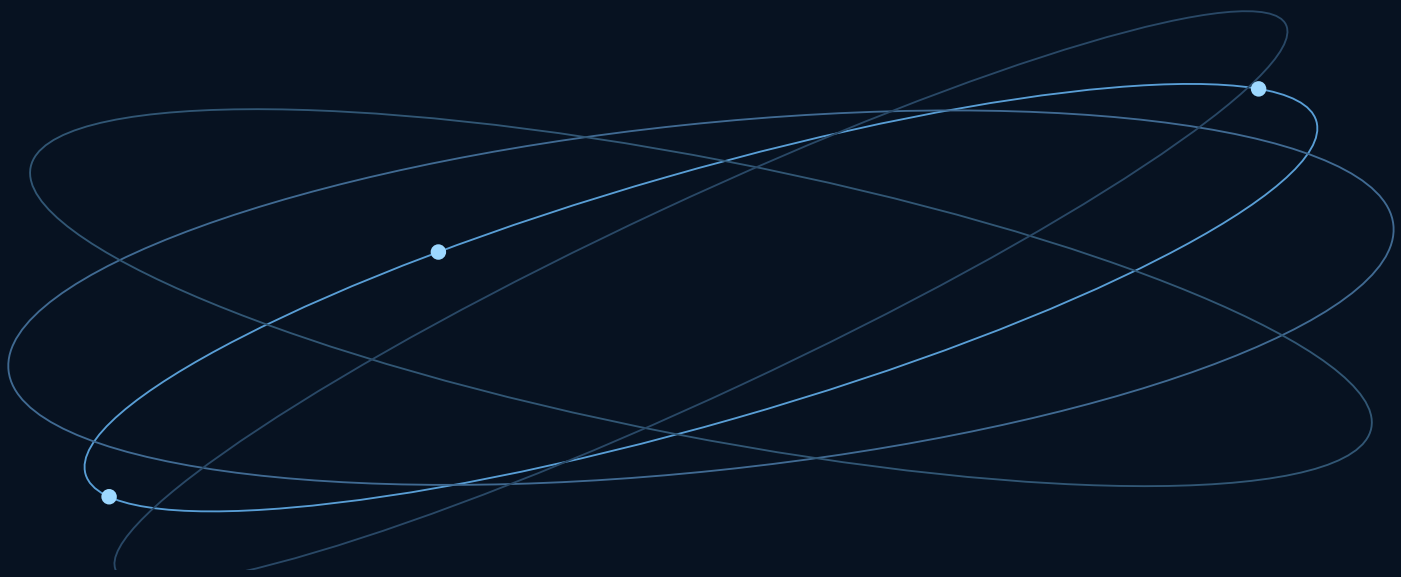
CONFERENCE PAPER

Introducing
SARA Constellation

Satellite for Agriculture and Remote Areas®

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Acosta Aerospace



PRESENTED AT

5th IAA Latin American CubeSat Workshop

3rd IAA Latin American Symposium on Small Satellites

7–11 November 2022

INTRODUCING SARA CONSTELLATION: SATELLITE FOR AGRICULTURE AND REMOTE AREAS®

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Keywords: Nanosatellite, Constellation, IoT/M2M, Remote Areas, Orbit design

This paper introduces the SARA Constellation for data telecommunication in re- mote areas. We investigate the performance of a 5-nanosatellite-based LEO constellation considering different designs and different locations in South America. To assess the performance of several constellation designs, we consider a scenario with four target locations and discuss four figures of merit such as *satellite availability*, *satellite time-in-view*, *coverage gap*, and *timing consistency*. Simulation results indicate enough coverage performance to meet our basic mission goals. We also provide a brief description of the overall mission requirements and the system architecture.

1. Introduction

Internet connectivity is considered a basic infrastructure in urban centers but is not the case in most remote and rural areas. In *Mato Grosso*, Brazil's largest soybean, cotton, and corn producer, internet connectivity is available in 86% of farms, but signal coverage runs in only 3% of production fields. A similar lack of connectivity is found in other remote areas such as borders, mining sites, and over oceans and large forests. With the advancement of space-qualified *components-off-the-shelf (COTS)*, and IoT- oriented technology for CubeSats, we have seen the development and deployment of nanosatellite-based LEO constellations for IoT service [1] [2].

In this paper, we introduce the SARA Constellation to provide IoT/M2M data telecommunication in remote areas. Our work presents preliminary trade-off results of SARA's R&D and its conceptual design phase. In the sequel, we give attention to the constellation design and analysis. We investigate constellation design candidates to fulfill our most basic mission premise, that is:

A constellation of nanosatellites to provide IoT telecommunication service to remote areas. The initial constellation shall consist of 5 satellites of the type 6U CubeSat operating in LEO. The constellation shall provide coverage primarily over the Brazilian territory, and the South American territory. The coverage shall also (i.) provide at least two accesses per day for all locations, and (ii.) be uniform. In the end, we describe our system architecture, providing a description of mission requirements, payload, and bus.

2. Constellation Design and Analysis

2.1. Orbit design

Let us begin by defining the *Walker Delta Pattern* (WDP) as the design framework. Among other frameworks, the WDP is of particular interest due to its symmetry, uniform distribution, and low complexity characteristics [3]. The WDP framework is essentially characterized by three integer parameters: *(i.)* the total number of N satellites evenly distributed over *(ii.)* the number of P orbital planes evenly spaced along the equatorial plane, and *(iii.)* the phasing parameter, $\delta\varphi$, between satellites of adjacent planes. Provided that our mission is restricted to 5 satellites in its initial fleet, we thus have two possible configurations based on WDP: *(i.)* a constellation of five

satellites evenly distributed over one orbital plane; or *(ii.)* a constellation with five evenly spaced orbital planes with one satellite per plane. We shall see that either configuration presents advantages and disadvantages, but can be complementary to each other, nonetheless.

Table 1: Design variable and constraints for SARA Constellation.

Variable	Concerns	Evaluation Criteria	Design Constraints	
N# of satellite, N	- Mission costs; and - Coverage capacity.	Minimize with respect to mission requirements.	5 satellites	
N# of planes, P	- Coverage enhancement; - Degradation; and - Mission costs.	Minimize with respect to mission requirements.	1 plane	5 planes
Configuration	- Coverage uniformity.	Select for best coverage and mission objectives.	WDP defined by N and P and orbit parameters h, i, e.	
Plane spacing, $\delta\Omega$	- Coverage uniformity.	Choose to best meet the mission requirements.	$\delta\Omega = 0^o$	$\delta\Omega = 72^o$
Sat. phasing, $\delta\varphi$	- Coverage uniformity.	Choose to best meet the mission requirements.	$\delta\varphi = 72^o$	$\delta\varphi = \{0,$
Eccentricity, e	- Mission complexity.	Choose to best meet the mission requirements.	$e = 0.001$	
Altitude, h	- Coverage quality; - Time in view; - Link budget; and - Launch costs.	*Performance vs. Costs.*	$h = \{500, 600, 700\}$ km	
Inclination, i	- Coverage quality; - Launch costs.	*Performance vs. Latitude* *Performance vs. Costs*	$50^o \leq i \leq 100^o$	

Other parameters of particular impact in a constellation performance are the altitude, inclination and eccentricity. Table 1 summarizes the most relevant design variables, along with evaluation criteria and constraints in our work. Given our mission objectives, circular orbits are preferred due to coverage and service uniformity. We assumed a rather practical figure eccentricity $e = 0.001$, as can be observed for operational LEO satellites with similar purposes. As for the altitude and inclination, the choice of these parameters must follow a trade-off of performance and mission budget, such as coverage quality and time in view against costs and different latitudes [4] [5]. Here, we assess the orbital parameters variation under J_2 perturbation due to the earth oblateness. From the *method of averaging [6]* we find that h, i and e, in average, are not affected, *i.e.*, $\Delta h = \Delta i = \Delta e = 0$, but such parameters have impact in the averaged variation of both the right ascension of the ascending node, Ω, and the argument of periapsis, ω. That is:

$$\Delta\Omega = -\frac{3}{2}\frac{n J_2 R_\oplus^2}{a^2\left(1-e^2\right)^2}\cos i \tag{1}$$

$$\Delta\omega = -\frac{3}{2}\frac{n J_2 R_\oplus^2}{a^2\left(1-e^2\right)^2}\left(\frac{5}{2}\sin^2 i - 2\right) \tag{2}$$

where: n is the mean motion; $R_\oplus \approx 6378.16$ km is the Earth mean equatorial radius; $a = r_p/(1-e)$ is the semimajor axis as function of the perigee radius, which we assume $r_p \equiv R_\oplus + h$, which h as our design altitude; and corresponds to the averaged variation.

Figure 1-(A,B) show the variation of Ω and ω, respectively, given $e = 0.001$ and varying values for altitude, $500\ km \leq h \leq 700\ km$, and inclination $0^o \leq i \leq 100^o$. It can be observed that $\Delta\Omega \to 0$ for highly inclined orbits as $i \to 90^o$, which tends to be favorable to coverage timing consistency. That is, the smaller the $\Delta\Omega$, the more timely consistent will be a satellite pass over a particular location. Ideally, $\Delta\Omega = 0$ for $i = 90^o$, yet this inclination is not recommended considering the scalability of the constellation as the probability of self-induced collisions over

the poles may increase with the growth of the constellation. From eq. (1), by setting , one can derive a family of *Sun-Synchronous Orbits (SSO)* with inclination ranging from 97^o to 98^o as function of altitudes from 500 km to 700 km. From eq. (2) when $\Delta\omega = 0$, one can derive the *Frozen Orbits (FRO)* defined by the critical inclination for all values of altitude. We have also considered in our analyses inclined orbits with $i = 50^o$, in this paper labelled as *i50* orbits, as it can also meet the coverage requirements over the Brazilian and South American territory. Table 2 provides information of the orbit designs considered in our work.

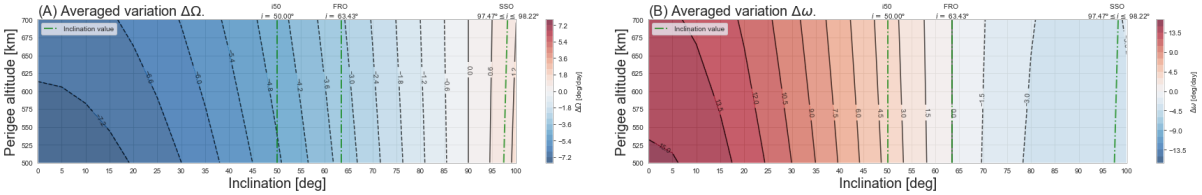


Figure 1: Averaged variations $\Delta\Omega$ and $\Delta\omega$ due to Earth's oblateness.

Table 2: Variation of parameters for Inclined, Frozen and Sun-Synchronous orbits.

Circular Orbit ($e = 0.001$)		**Inclined Orbit**	**Frozen Orbit**	**SSO**	
$h = 500.0$	km	$i = 50.0$	$i = 63.43$	$i = 97.43$	deg
$T = 94.76$	min	$\Delta\Omega = -4.90$	$\Delta\Omega = -3.41$	$\Delta\Omega = 0.99$	deg/day
$n = 15.20$	rev/day	$\Delta\omega = 4.06$	$\Delta\omega = 0.00$	$\Delta\omega = -3:49$	deg/day
$h = 600.0$	km	$i = 50.0$	$i = 63.43$	$i = 97.79$	deg
$T = 96.69$	min	$\Delta\Omega = -4.66$	$\Delta\Omega = -3.24$	$\Delta\Omega = 0.99$	deg/day
$n = 14.89$	rev/day	$\Delta\omega = 3.86$	$\Delta\omega = 0.00$	$\Delta\omega = -3.30$	deg/day
$h = 700.0$	km	$i = 50.0$	$i = 63.43$	$i = 98.19$	deg
$T = 98.77$	min	$\Delta\Omega = -4.43$	$\Delta\Omega = -3.08$	$\Delta\Omega = 0.99$	deg/day
$n = 14.58$	rev/day	$\Delta\omega = 3.68$	$\Delta\omega = 0.00$	$\Delta\omega = -3.11$	deg/day

Having the orbit types *i50*, *FRO*, and *SSO* as reference, we have iterated the altitude taking into account $\Delta\Omega$ and the rotation of the Earth to obtain repeating track orbits for a reference mean motion value. Figure 2 shows the mean motion for a range of altitudes for *i50*, *FRO*, and *SSO* designs and the intersection where $n = 15\ \ rev/day$, that is: $h \approx 609.0\ \ km$ for *i50* orbits; $h \approx 590.0\ \ km$ for *FRO* orbits; $h \approx 535.0\ km$ for *SSO* orbits, with $i \approx 97.56^o$. Therefore, considering the design variables in Table 1 and having defined the orbit parameters, Figure 3 shows our constellation design candidates breakdown for SARA Constellation.

2.2. Coverage assessment

Following analytic approximations in [4], one can assess the coverage percentage against latitude for a range of inclination values. For the proposed mission, we assume that the contact between target and satellite is established at a minimum elevation angle $\varepsilon_{min} \equiv 15^o$. Assuming altitude $h \equiv 500.0\ \ km$, the maximum *earth central angle*, λ_{max}, and the maximum range, d_{min}, are:

$$\lambda = 90^o - \varepsilon_{min} - \eta_{max} \approx 11.4^o \tag{3}$$

$$d_{max} = R_\oplus \frac{\sin \lambda_{max}}{\sin \eta_{max}} \approx 1407.52 \ \ km \tag{4}$$

with $$\sin \eta_{max} = \sin\left(\frac{R_\oplus}{R_\oplus + h}\right) \cos \varepsilon_{min} \tag{5}$$

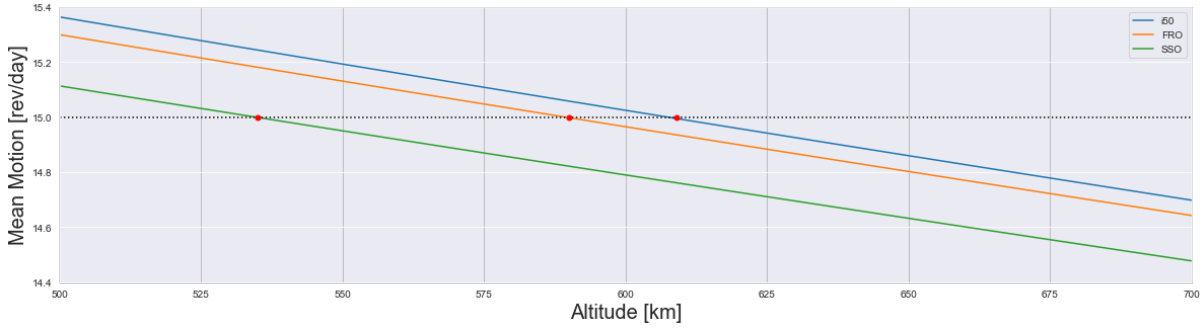


Figure 2: Mean motion against altitude for *i50, FRO,* and *SSO* designs.

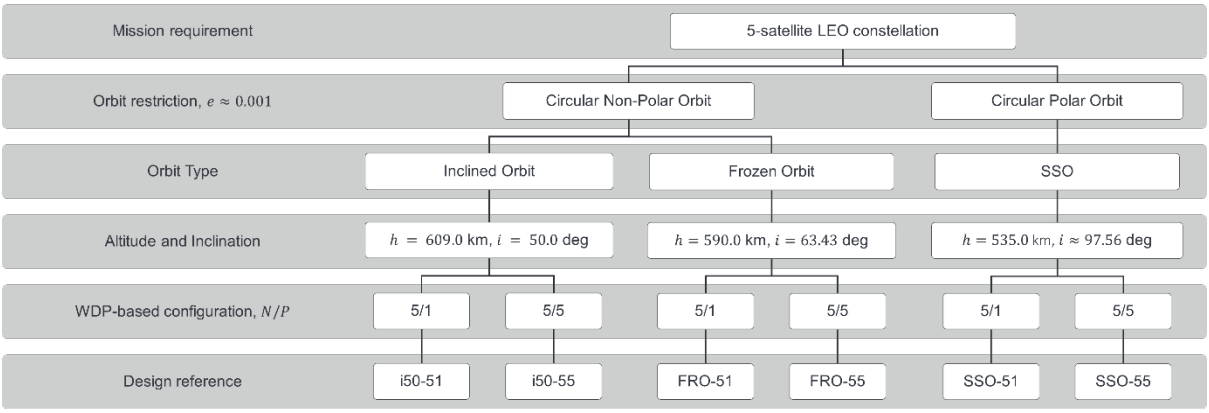


Figure 3: Constellation design breakdown.

where η is referred to as the *nadir angle* between the satellite nadir and the line-of-view to target. Eqs. (3)-(4) estimate that a satellite will be in range of contact at a maximum distance of $1407.52 \ \ km$ to a target within the *swath width* of $2\,\lambda_{max}$.

Figure 4 shows the *coverage percentage (CP%)* for a series of inclination values against latitude [4]. Our goal is to assess the coverage performance for the *i50, FRO,* and *SSO* designs represented by the dash-dotted line according to the orbit inclination. Observed advantages and disadvantages are:

1. the coverage requirement over the Brazilian and South American territory is met as both *i50, FRO,* and *SSO* designs lie within the region constrained by the dotted and dashed horizontal lines with $CP\,\% \ > \ 0$;
2. non-polar, inclined orbits, such as *i50* and *FRO,* designs provide more $CP\,\%$ compared to the *SSO* orbits, yet coverage degrades at very high latitudes;
3. polar orbits, such as *SSO* design, can provide global coverage, yet coverage degrades at low latitudes.

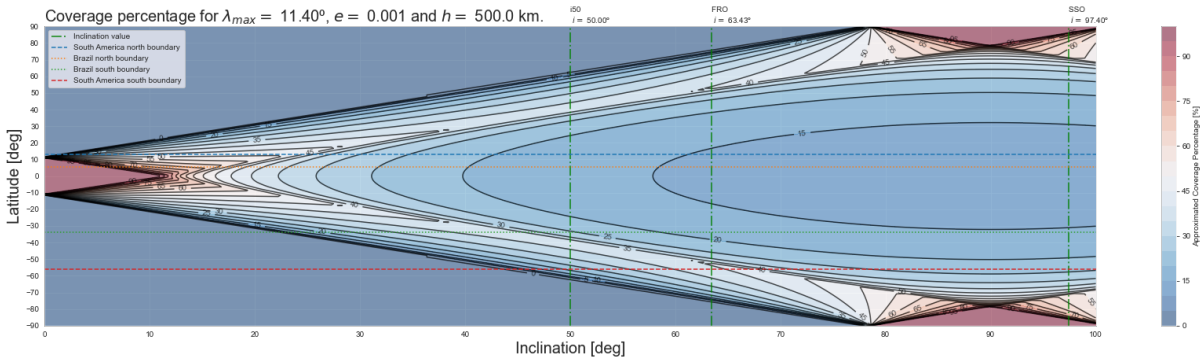


Figure 4: Approximated coverage percentage for a range of inclination values.

Next, we present simulation results for several constellation designs.

2.3. Simulation Results

In this section, we discuss the simulation results for different constellation designs (*cf.* Figure 3) and scenarios considering some locations of interest across the South American territory, as given in Table 3 and Figure 5. Simulations were all run using STK® for a time span from *01 January 2022 01:00:00.0 UTCG* to *30 April 2022 23:59:59.0 UTCG*. Next, we compare the performance of our constellation designs in terms of four figures of merit: *(i.) satellite availability*, *(ii.) satellite time-in-view*, *(iii.) coverage gap*, and *(iv.) timing consistency*.

Table 3: Examples of reference locations.

Location	Country	Latitude	Longitude
Location 1	Brazil	06.041 S	50.177 W
Location 2	Peru	10.215 S	76.379 W
Location 3	Brazil (off-shore)	21.238 S	39.963 W
Location 4	Argentina	48.383 S	68.264 W

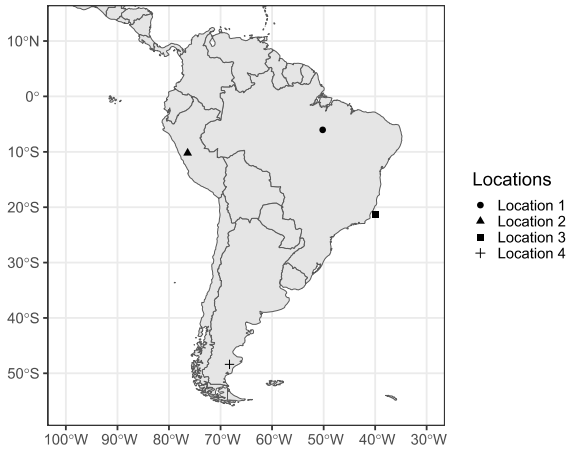


Figure 5: South America view and reference locations.

2.3.1. Satellite availability assessment

We begin by assessing the satellites daily availability, *i.e.*, the number of contacts over a target location. Figure 6 shows the averaged contact count per weekday for each SARA (*i.e.*, *SARA-01*, *02*, ..., *05*) over the target locations (by rows) for each constellation design (by columns). We can observe that all SARAs accomplished a contact pass, in average, more than twice a day for all designs. Also, we can see that all designs account more contact passes at very high latitudes, such

as location 4, and low-inclination designs, such as *i50* and *FRO*, are more likely to account more contacts than polar-orbit-based designs, as *SSO*, for most scenarios.

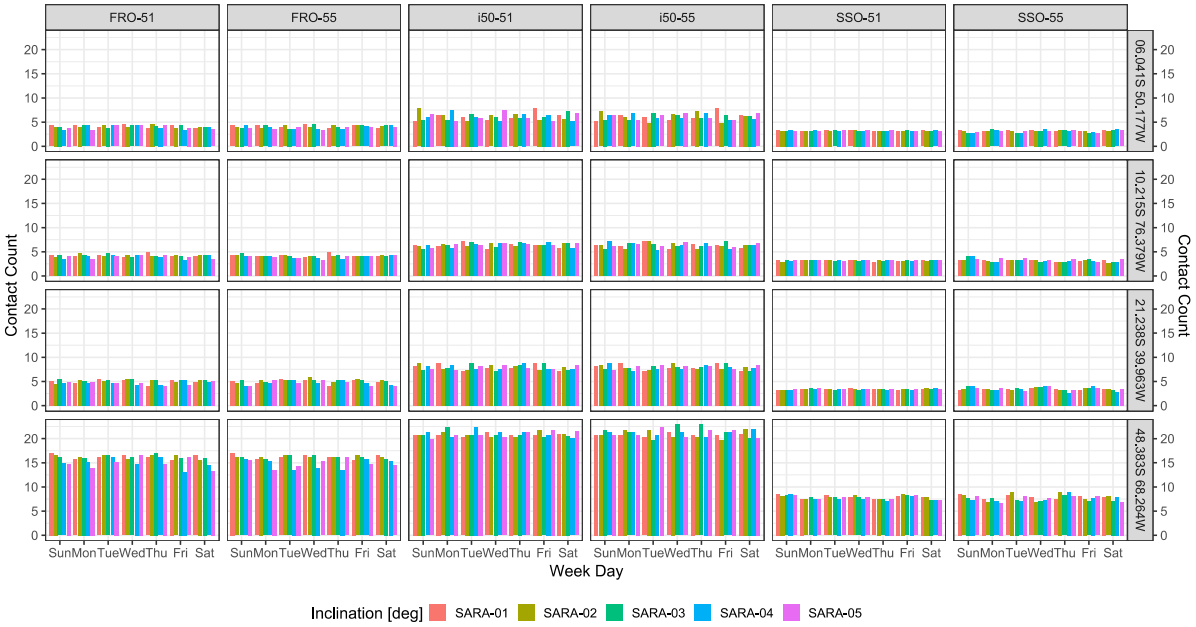


Figure 6: Overall number of contact passes breakdown.

2.3.2. Satellite time-in-view and coverage gap assessment

Time-in-view refers to the time within which a target on the ground is seen by a satellite above the minimum elevation angle, *i.e.*, $\varepsilon_{sat} > \varepsilon_{min}$. Whenever the satellite is out of range, the time to the next contact is accounted as a gap in coverage. Figures 7 and 8 compare *time-in-view* and *coverage gap* duration for all constellation designs over our target locations (*cf.* Table 3). Figure 7 shows that all proposed designs provided a mean time-in-view above 4 minutes. According to our designs (*cf.* Figure 3), those of higher altitudes provide longer time-in-view exposures. As for coverage gaps, in Figure 8, we can compare coverage performance and degradation. As discussed in Section §2.2, coverage degrades for higher inclination over lower latitudes.

2.3.3. Timing consistency assessment

Timing consistency here refers to the regular availability of the satellites every day. Taking the time-in-view peak hour as reference, *i.e.*, when the satellite is at the minimum distance from the target location, Figure 9 shows the time of contact for each SARA over *Location 1* (*cf.* Table 3), for each design inclination and configuration. In contrast to the results for the previous figures of merit, here we can note that SSO- based constellations are more consistent compared to the other designs. Because of greater $\Delta\Omega$ induced by lower inclinations, satellites will be in view in different times each day. Especially for the 5/1 configuration, this can pose disadvantages to time- sensitive service. Another aspect to note is the impact of the configuration. While the 5/5-based constellations feature better distribution during the day, the 5/1-based constellations rather concentrate contacts during short time windows of the day. The latter, however, especially for the *SSO* design, may grant robustness to the service provided. That is, in case of a satellite loss, service can still be provided by the other satellites. Also, when considering the scalability of the constellation, we identify that those uncovered time windows could be mitigated as more fleet of satellites are being added to the constellation in complementary orbital planes.

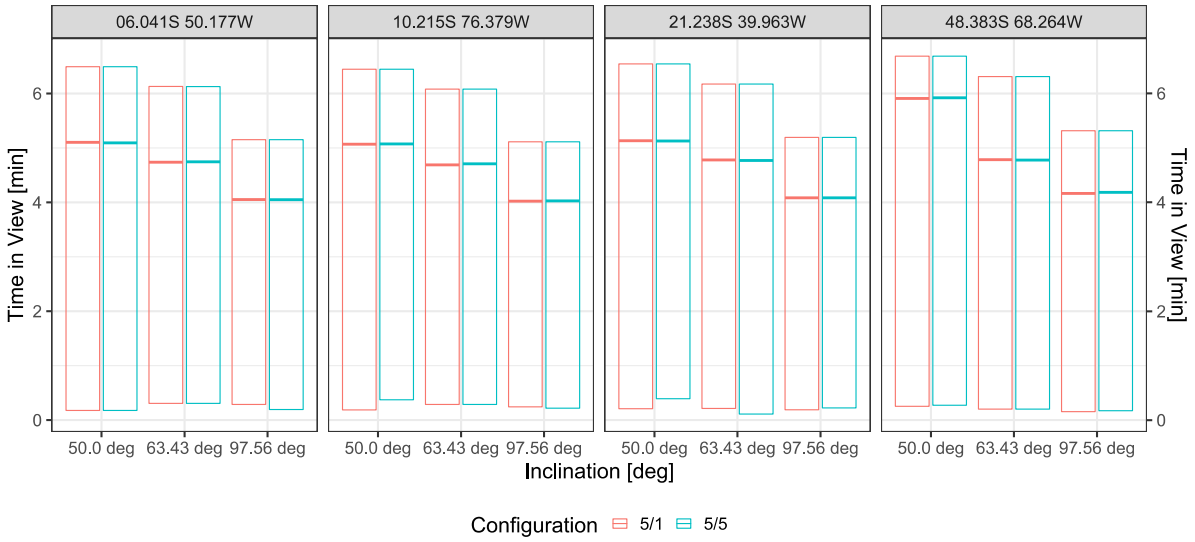


Figure 7: Overall comparison of time-in-view over locations.

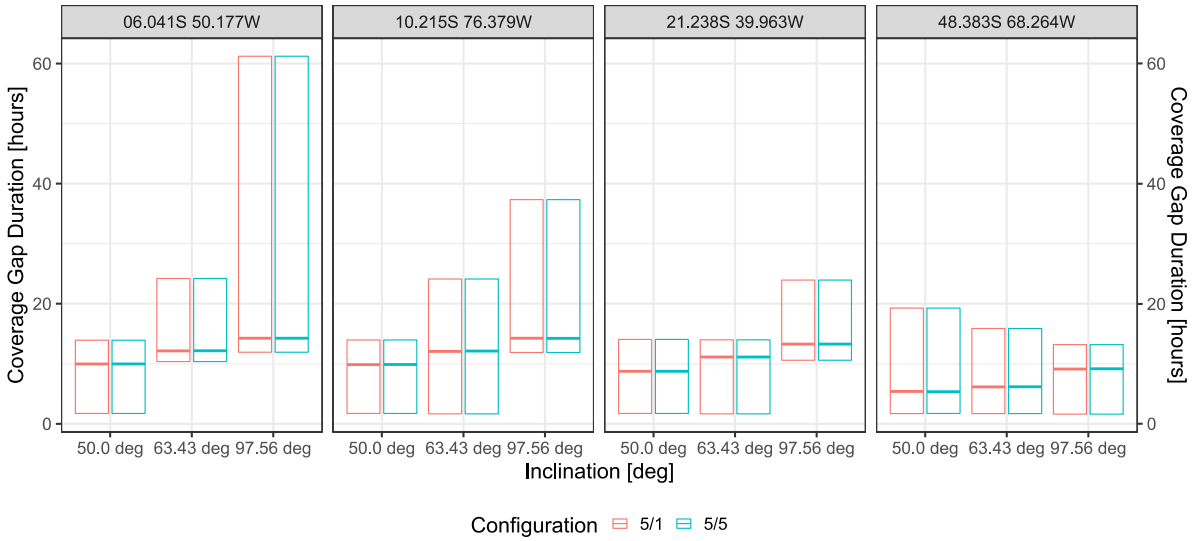


Figure 8: Overall comparison of coverage gap duration over locations.

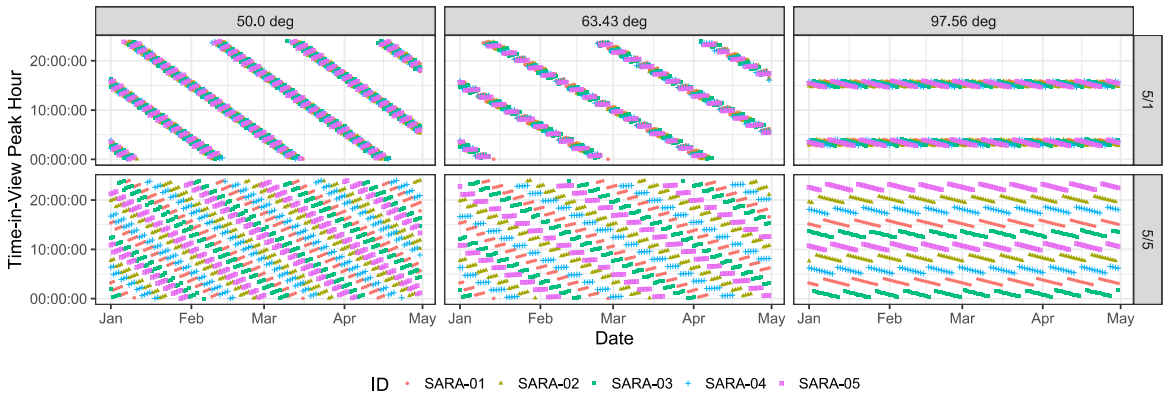


Figure 9: Daily time-in-View peak hour over Location 1.

3. System Architecture for SARA

The proposed SARA Constellation is made up of five nanosatellites dedicated to providing IoT/M2M connectivity for agriculture operations and remote area monitoring. Essentially, the constellation will receive telemetry from M2M terrestrial networks, delivering it to the end-users via the internet, enabling continuous monitoring and rapid response in critical scenarios. The individual satellites and the constellation architecture are under development following the requirements shown in Table 4.

3.1. Satellite payload

Our system design considers a multifunctional constellation for data telecommunication. That is, in order to leverage the full potential of a LEO constellation, SARA integrates multiple payloads as described in Table 5.

Table 4: Top-level mission requirements for SARA Constellation.

Functional	Performance	A fleet of 5 nanosatellites of type 6U; Capacity of multi-access for IoT devices
	Coverage	Daily access windows; Brazilian and South American territory
	Responsivity	Store & Dump
	Payload	IoT and vehicle monitoring
Operational	Lifetime	< 5 years per satellite
	Availability	Minimum of two accesses daily for all location
	Survivability	LEO qualified; Collision-free; Corrective maneuvering
	Payload data transmission	Transmission to ground stations
	Throughput	Packages of up to 1 MB
	Target	IoT/M2M devices, data collection, platforms, transponders.

3.2. Satellite bus

The SARA Constellation service module is COTS-based, designed to accommodate a state-of-the-art ADCS, a high-capacity AI-enabled internal storage system, a high-performance OBDH, and a micro propulsion system to enable small orbit corrections and deorbiting at the end of life. Table 6 describes the overview of the expected bus for SARA.

4. Conclusion

We have introduced the SARA Constellation under development to provide data telecommunication service in remote areas, focusing on the Brazilian and South American territory. Our proposed constellation considers an initial fleet of 5 nanosatellites 6U standard. We have investigated several constellation designs assuming the Walker Delta Pattern framework, a range of altitudes and inclinations. Coverage performance of the proposed designs over four target locations across the South American territory are then compared in terms of different figures of merit. In some aspects, such as satellite availability and gap coverage, non-polar-orbit-based designs presented better performance than the polar-orbit-based designs. However, for daily timing consistency, polar-orbit-based designs presented better performance. As for the system architecture for SARA Constellation, we have presented a description of the characteristics of the satellite.

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Table 5: Payload for SARA Constellation.

Service	RF band	Performance
IoT/M2M	Tx/Rx: S band Tx: X band (TBD)	1.0–100.0 Mbps 100.0–200.0 Mbps
Vehicle Monitoring	Rx: UHF band	9.6–38.4 kbps

Table 6: Bus description for SARA Constellation.

Subsystems		Specification
ADCS	Objective: Attitude control: Attitude determination:	Active 3-axis stabilization and control. 3-axis reaction wheels and 3-axis magnetorquers suite; 3-axis Gyroscope, Star-tracker, Sun sensors, Magnetometers suite.
Propulsion		Low-thrust propulsion for small orbit corrections and end-of-life deorbiting.
OBDH		High performance onboard computer and massive data storage.
TMTC	Modules: Antennas:	UHF-band primary comms. and S-band secondary comms. Deployable UHF antennas and S-band patch antennas.
Structure		6U standard equipped with deployable solar panels.
Thermal control		Passive control. EPS-integrated active monitoring and control.
Power	Primary: Secondary: PCDU:	Deployable solar panels; Minimum of 10 W. Li-ion batteries; Minimum capacity: 1 Ah. Regulated/non-regulated bus; MPPT control; Parallel recharge;

Acknowledgments

This work is partially supported by FAPESP grant no. 2020/05196-4, and CNPq grant no. 424198/2021-5.

References

[1] Z. Yoon, W. Frese and K. Briess, "Design and Implementation of a Narrow-Band Intersatellite Network with Limited Onboard Resources for IoT," *Sensors,* vol. 19, no. 19, p. 4212, 2019.

[2] Z. Qu, G. Zhang, H. Cao and J. Xie, "LEO Satellite Constellation for Internet of Things," *IEEE Access,* vol. 5, pp. 18391-18401, 2017.

[3] J. J. Davis e D. Mortari, “Reducing Walker, Flower, and streets-of-coverage constellations to a single constellation design framework,” *Advances in the Astronautical Sciences,* vol. 143, pp. 697-712, 2012.

[4] J. R. Wertz and W. J. Larson, Space Mission Analysis and Design, 3rd ed., Microcosmo Press & Kluwer Acaemic Publishers, 1999.

[5] S. Huang, C. Colombo and F. Bernelli-Zazzera, "Multi-criteria design of continuous global coverage Walker and Street-of-Coverage constellations through property assessment," *Acta Astronautica,* vol. 188, pp. 151-170, 2021.

[6] H. D. Curtis, Orbital Mechanics for Engineering Students, 3rd ed., Butterworth-Heinemann, 2014.