Constellation Design of Remote Sensing Small Satellite for Infrastructure Monitoring in India

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ABSTRACT

A constellation of remote sensing small satellite system has been developed for infrastructure monitoring in India by using Synthetic Aperture Radar (SAR) Payload. The low earth orbit (LEO) constellation of the small satellites is designed in a way, which can cover the entire footprint of India. Since India lies a little above the equatorial region, the orbital parameters are adjusted in a way that inclination of 36 degrees and RAAN varies from 70-130 degrees at a height of 600 km has been considered. A total number of 4 orbital planes are designed in which each orbital plane consisting 3 small satellites with 120-degrees true anomaly separation. Each satellite is capable of taking multiple look images with the minimum resolution of 1 meter per pixel and swath width of 10 km approx. The multiple look images captured by the SAR payload help in continuous infrastructure monitoring of our interested footprint area in India. To support the mission, each small satellite is supplied with earth sensors, sun sensors, GPS to accurately determine its position and attitude, and Control Moment Gyro which is capable of high slew rate maneuver with precise pointing at minimum power utilization. Further, each small satellite is equipped with a communication payload that uses X-band and VHF antenna, whereas the TT&C will use a high data-rate S-band transmitter. The satellite requires a powerful set of batteries to operate along with an origami-designed solar panel with the implementation of GaN-FETs to improve the performance and efficiency of solar power conversion. The paper presents only a coverage metrics analysis method of our designed constellation for our India footprint by considering the important metrics like revisit time, response time, and coverage efficiency. The data processing for the captured images is not presented here. The result shows that the average revisits time for our constellation ranges from about 15- 35 min which is less than an hour and the average response time for this iteratively designed constellation ranges from about 25-120 min along with hundred percent coverage efficiency most of the time. Finally, it was concluded that each satellite has 70kg of total mass and costs around $ 0.75M to develop.

INTRODUCTION

In the recent decade, the satellite constellation idea has evolved broadly, with huge satellites operating in space to fulfill the required application demand. It is used to permanently provide communication facilities and global coverage at anytime, anywhere on the earth. The access to space is continuously increasing due to the design and technology miniaturization of large satellites to small satellites and an increase in small satellites' launch rate from Femto to Mini size. Moreover, their constellation is getting tremendous attention these days for sustainable business purposes. The upcoming decade is IoT, edge computing, weather science, disaster monitoring, and safety security, which will have the most significant potential and dependency in the satellite constellation development for the business purpose. Remote sensing is one of the most famous applications in satellite technology for the development of technology like infrastructure, disaster, weather, biodiversity, forestry, surface change, and agriculture monitoring purpose. Previously, most of the constellations used to be at Sun Synchronous Orbit or High Earth Orbit for remote sensing and earth observation with larger satellites. But in recent trends, most of the satellite constellation is often deployed at Low Earth Orbit, as the single satellite only covers certain small areas of the earth that orbit at higher angular velocity to maintain its orbit. Therefore, numerous LEO satellites are required to provide continuous permanent global coverage.

In this paper, we will present our work in each section. The section consists of constellation design, preliminary sizing of the satellites, coverage quality measurement, results, and discussion of our simulated case and overall conclusion. The constellation design represents the iterative design procedure of selection of our orbital parameters and orbital plane, which will be capable of making overall coverage of our area of interest footprint. Whereas the preliminary sizing section represents the distribution of the mass and cost budget of each sub-system of the satellites and their selection of the optimal components required while making a full working satellite. This section also represents our SAR payload specification which is required to take multiple images while passing over India. The coverage quality measurement section explains the method of finding the different coverage metrics and mathematical models involved in it along with the importance of the coverage performance of our designed constellation. The image and data processing for the captured images is not presented in this paper as it will be done by other groups. The result and discussion section shows the important results of some coverage metrics parameters which are required to evaluate the coverage performance of our constellation. Finally, all the section is concluded in the conclusion section.

CONSTELLATION DESIGN

we had presented LEO small satellite constellation design in an iterative way, which will be capable of capturing the entire footprint coverage of the India location in 24-hour duration. Each small satellite consists of a SAR payload system which enables to capture of the footprint at each revisit to the India location. The iterative design of the satellite constellation and orbital parameter were run on the AGI STK tools by considering the SGP4 orbital propagator to minimize the positional and attitude discrepancy. The selected orbital elements and the number of the satellite in each orbital plane are shown in Table 1. The schematic diagram of a small satellite constellation having 4 orbital planes with 3 satellites at each plane along with the India footprint is shown in figure 1. Figure 2 represents the ground track of the satellite to the India location along with the access coverage which is marked by the red color.

Table1. Small Satellite Constellation Orbital Parameters.
(Whereas G1, G2, G3, and G4 are the individual orbital planes.)

	Parameters	G1	G2	G3	G4
1.	Height	600 km	600 km	600 km	600 km
2.	Inclination (i)	36°	36°	36°	36°
3.	RAAN	70°	90°	110°	130°
4.	No. of Satellites	3	3	3	3
5.	True Anomaly Separation	120°	120°	120°	120°

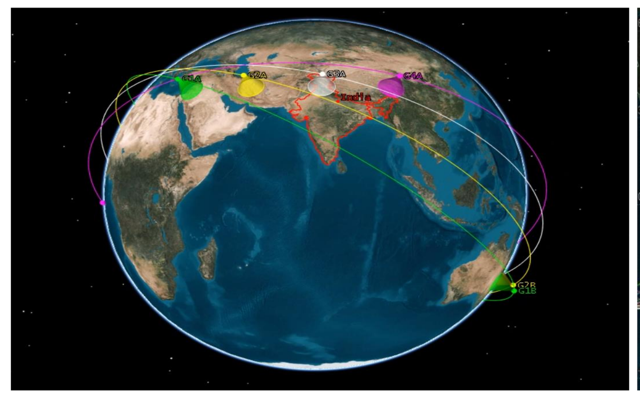

Figure 1: Constellation design visualization in 3D space.

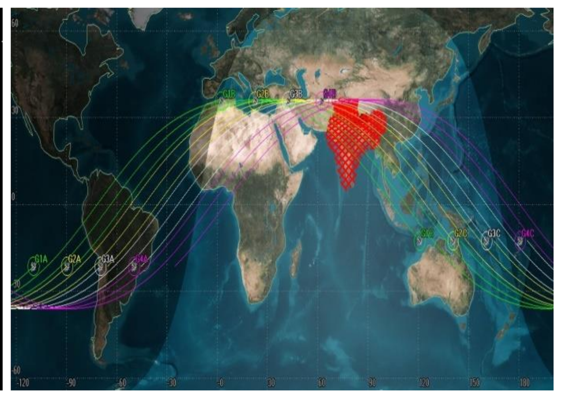

Figure 2: Coverage access in India footprint.

PRELIMINARY SIZING OF THE SATELLITES

The design of the satellite always starts with the conceptual and type of payload is used for the mission. The selected component of each sub-system is shown in the form of the UML diagram and the mass budget for our SAR payload satellites is shown in Table 2. The specification of our InfraSat payload is shown in Table 3.

Table 2: InfraSat's Mass and the Cost budget.

Sub System	Mass [Kg] (% of total)	Cost Budget (Lakhs) (% of total)
Structures	10.55 (15.10%)	53 (9.62%)
ADCS	3.21 (4.60%)	78 (14.15%)
Thermal	2.92 (4.17%)	20 (3.63%)
Power	16.57 (23.70%)	95 (17.24%)
Communication	2.60 (3.71%)	61 (11.07%)
C &DH	2.25 (3.22%)	54 (9.8%)
SAR Payload	25.50 (36.48%)	130 (23.60%)
Propulsion	5.50 (7.87%)	20 (3.63%)
Sub-total Integration	0.8 (1.14%)	10 (1.81%)
Miscellaneous	-	30 (5.44%)
Total	**69.90 (100%)**	**551 Lakh (100%)**

Table 3: Specification of InfraSat SAR payload.

Item	Specifications
Sensor	Optical
Sensor frequency	X-band
Antenna type	Mesh reflector
Observation Mode	Spotlight mode
GSD	<0.5/2 m (multi from 600 km)
Polarization	Linear
Resolution	~1m
Swath	10 km (spotlight mode)
Data transmission	X-band, 500Mbps, 10QAM
Bandwidth	200 MHz
Imaging time per orbit	3 min
Altitude	600 km (Nominal)
Design life	4 years

COVERAGE QUALITY MEASUREMENT

To calculate the satellite coverage towards India's footprint, the different satellite coverage characteristics and its performance parameters need to be determined. The coverage characteristic consists of coverage quality or metrics as the preliminary requirement which will address the ground track across our area of interest footprint. The coverage metrics help us to investigate the regional or global coverage provided by one or more satellites by considering all the access times of the satellites. The schematic block diagram to find the coverage characteristics and parameters for our India location AOI is shown in figure 3. The schematic diagram of the discretized grid for the India location is shown in figure 4. Equation 1-5 represents the mathematical expression of coverage, revisit and response time.

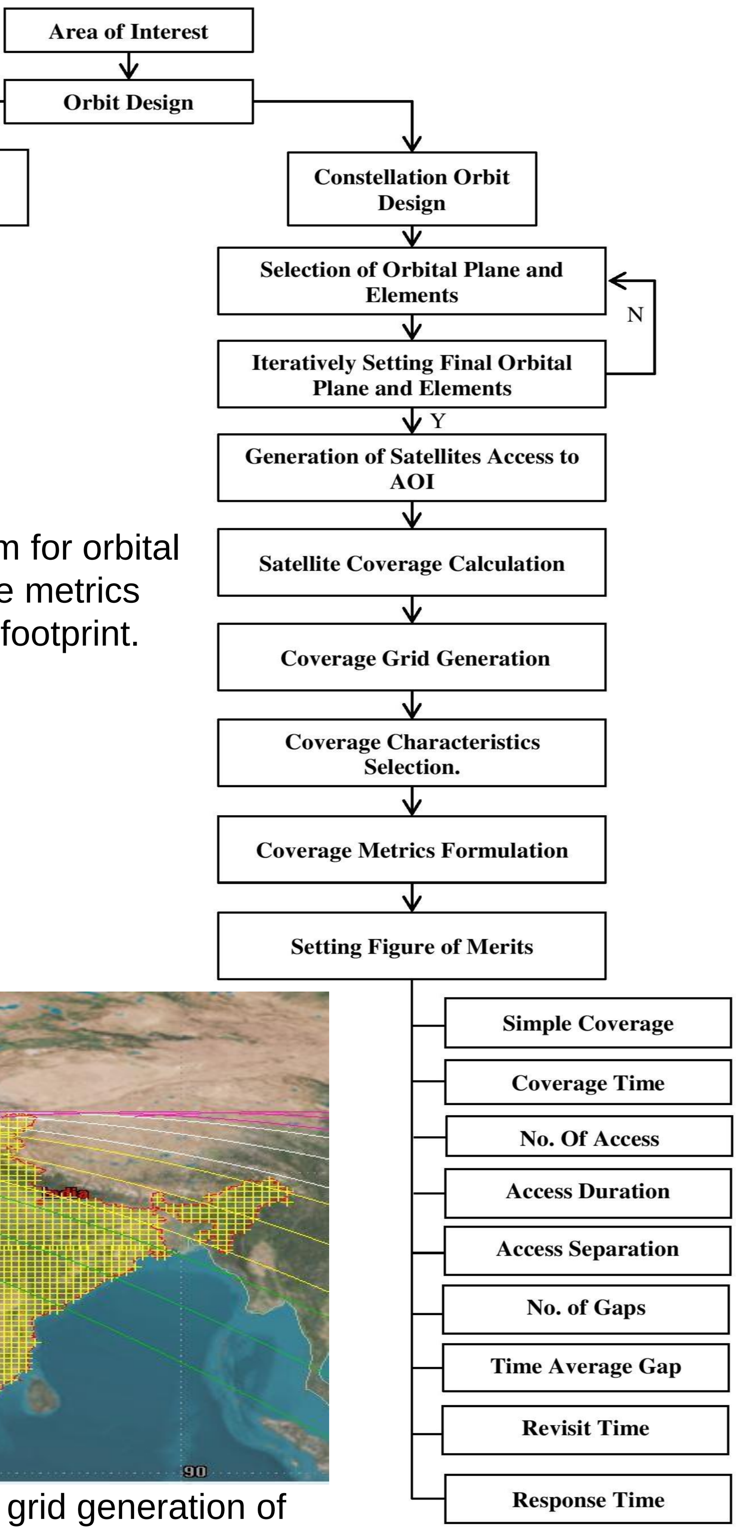

Figure 3: Block diagram for orbital design and coverage metrics calculation for India footprint.

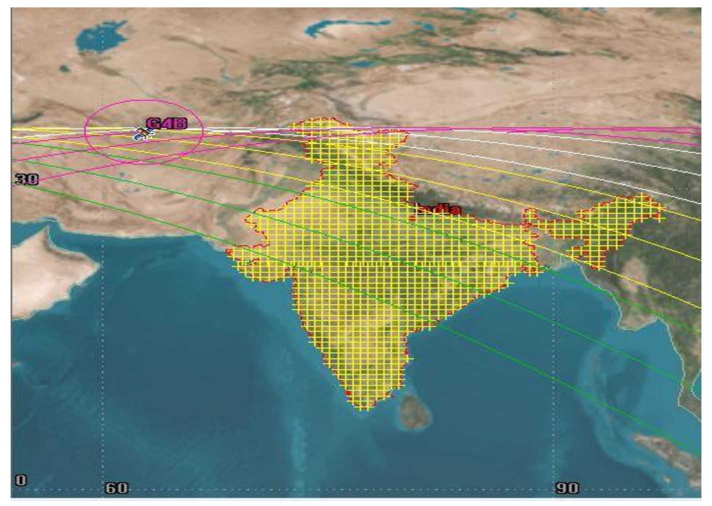

Figure 4: Coverage grid generation of India footprint with 0.5°discretization along lat-longs.

$$T_{c,total} = \sum_{i=1}^{N} T_c(i) \qquad (1)$$

$$T_{c,mean} = \frac{T_{c,total}}{N} \qquad (2)$$

$$T_{c,max} = max\{T_c(i)\} \qquad (3)$$

Where, $T_{c,total}$, $T_{c,mean}$, $T_{c,max}$ and T_c represents the total, mean, maximum, and single coverage time. N and i represent the total number of the coverage duration in i-th time. If the maximum coverage time is larger, there will be enough time to capture an image for infrastructure monitoring.

$$T_{R,av} = \frac{1}{N} T_c(i) \qquad (4)$$

Where, $T_{R,av}$ represents the average revisit time duration of the satellite.

$$T_{Re,av} = \frac{T_{Av,gap}}{2} \qquad (5)$$

Whereas, $T_{Av,gap}$ represents the time average gap.

Out of all the coverage metrics, the coverage time, revisit time, and response time are the major requirements for most of the infrastructure monitoring remote sensing satellites. These metrics help in determining the coverage characteristic performance of the constellation satellites. The satellite constellation can get the benefit of the higher coverage time and short revisit time to the given area of interest (AOI).

RESULTS

Out of all the coverage metrics, the revisit time, response time, and percentage coverage are the most important metrics for our analysis. So, we had found these metrics based on our constellation design by considering the SAR payload. The schematic diagrams of revisit time and response time along latitude and longitudinal location of India footprint are shown in figure 5 & 6 and figure 7 &8. Figure 9 and 10 represent the contour diagram of average revisit and response for India footprint. Whereas the coverage efficiency over the simulation time is shown in figure 11.

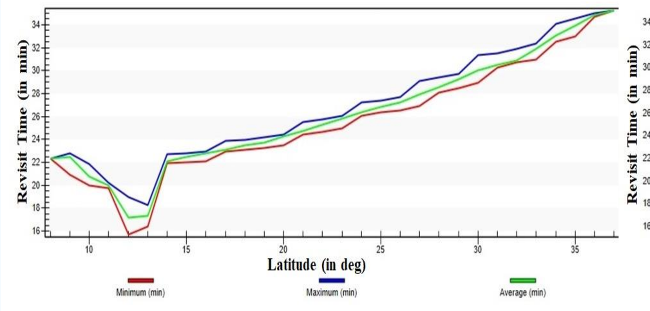

Figure 5: Graph of revisit time (in min) across latitude (in degree).

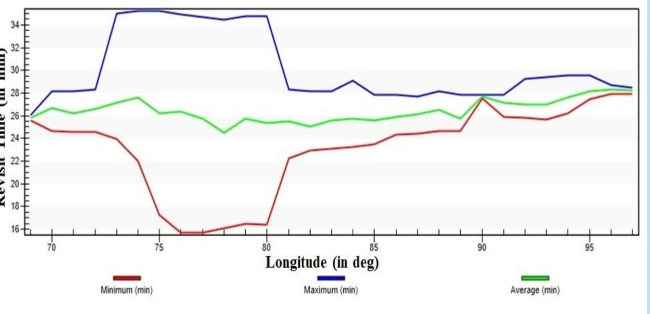

Figure 6: Graph of revisit time (in min) across longitude (in degree).

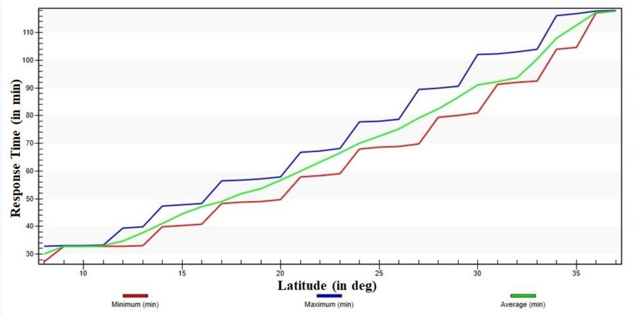

Figure 7: Graph of response time (in min) across latitude (in degree).

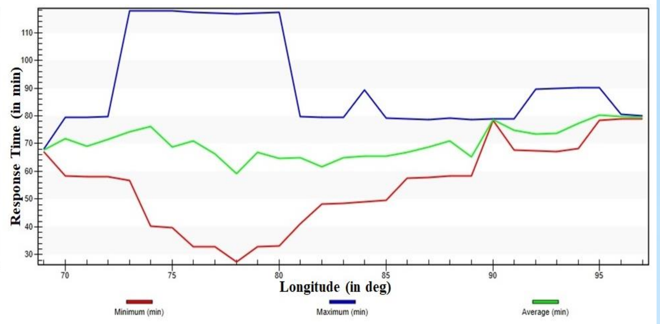

Figure 8: Graph of response time (in min) across longitude (in degree).

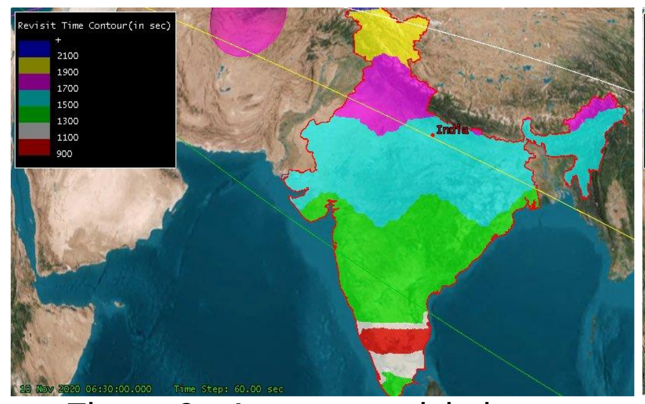

Figure 9:- Average revisit time contour across the footprint.

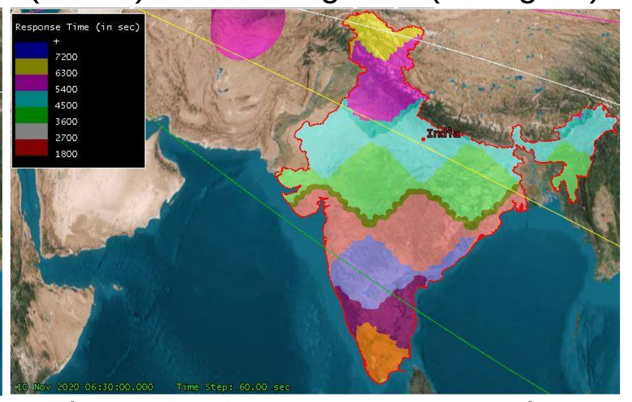

Figure 10: Average response time contour across the footprint.

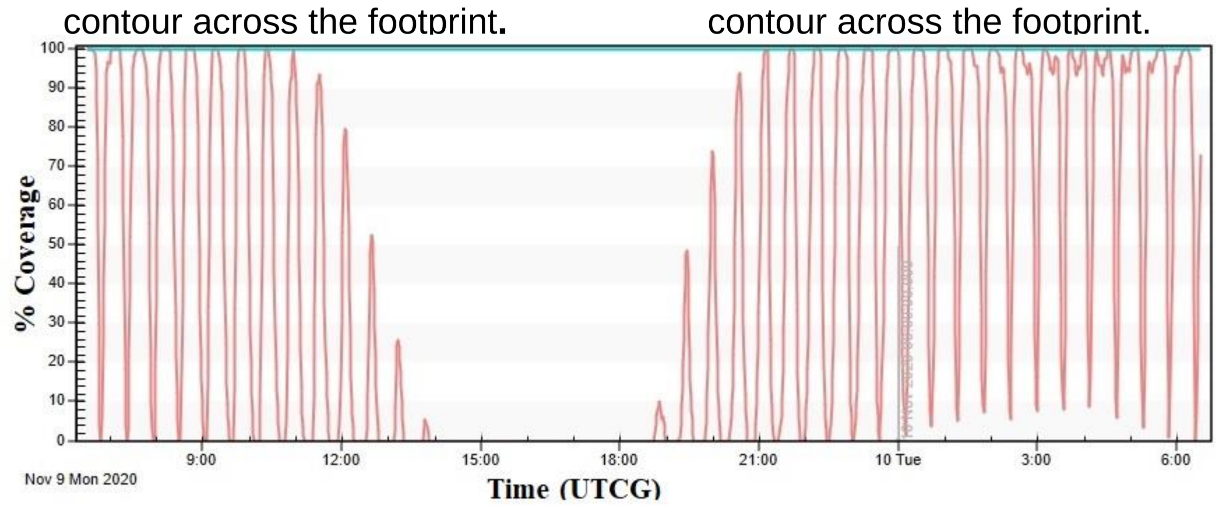

Figure 11: Graphical representation of % coverage across the simulation time (in UTCG).

CONCLUSION

A constellation of the small satellites for infrastructure monitoring has been designed by using the SAR as a payload. This constellation will be developed at LEO orbit which will cover an entire footprint of India location. Each orbital plane contains the 3 satellites and a total of 12 satellites will be operating. The orbital parameters are adjusted in a way that inclination of 36 degrees and RAAN varies from 70-130 degrees at a height of 600 km has been considered, which will be capable of making overall coverage of our India's footprint. Each InfraSat estimates a cost budget of about $ 0.75 M with an approximate of 70 kg mass budget. It will have a life span of 4 years and make continuous coverage across India. The coverage quality measurement section had described coverage metrics method and mathematical models involved in it along with the importance of the coverage performance. The coverage quality metrics were determined and essential metrics were calculated for the allocated footprint. Out of all the coverage metrics, the revisit time, response time, and coverage efficiency are the primary requirement to determine the coverage performance of the constellation. For our footprint, we found that the average revisits time for our constellation ranges from about 15- 35 min which is less than an hour. And the average response time for this iteratively designed constellation ranges about 25- 120 min. Similarly, for the same constellation, we mostly got a hundred percent coverage efficiency most of the time.