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Constellation Design and Orbit formation for SmallSat Platform for Earth Observation Mission

Samridh Patial[1], Aman Kumar Panda[2], Chesler Thomas[3], Sahil Bhatia[4], Sanjana Vajjala[5], Alok Mishra[6]

[1]*University of Petroleum and Energy Studies, Dehradun, India, patial.sam@gmail.com*
[2]*University of Petroleum and Energy Studies, Dehradun, India, aman.panda143@gmail.com*
[3]*University of Petroleum and Energy Studies, Dehradun, India, cheslerthomastk@gmail.com*
[4]*University of Petroleum and Energy Studies, Dehradun, India, sahil2112b@gmail.com*
[5]*University of Petroleum and Energy Studies, Dehradun, India, vajjalasanjana@gmail.com*
[6]*University of Petroleum and Energy Studies, Dehradun, India, alok11112@gmail.com*

Abstract

This paper outlays constellation design and orbit formation for SmallSats for earth observation mission and review of Small Sat platforms presently used by government space organizations and aerospace corporation. The earth observation mission's focus is to cover primary disaster prone and densely populated areas. The paper primarily addresses the constellation formation and orbit layout designed in way to provide high revisit frequency, maximum coverage area per orbit and minimum repeat cycle and standard Small Sat platform review on which various types of COTS remote sensing equipment can be used depending on the type of earth observation mission.

1. Introduction

The exploration of space has vastly improved our understanding of our planet Earth. From observing movements of clouds, communications, global positioning system to observing disaster, Mars orbiter and deep space exploration, space provides an endless space endeavour to explore and study. The primary tools which help us to observe and study space are the satellites. Satellites comes in various shapes and sizes with varied functionalities. Large satellite support state-of-art remote sensing payload, high bandwidth communication equipment and top of the line science experiments but this machinery is not a cost-effective one. Large satellite requires large amount of funding for build and launch, critical machining, lengthy development and testing time. On the other hand, SmallSats are way more economical compared to large satellites and with the advent of commercial-off the shelf equipment and additive manufacturing techniques, the cost of manufacturing is reduced to a further extent. Compared to the large satellites, SmallSats have limitation in case of effective swath area covered by the satellite and resolution is also largely affected to due considerable size reduction. Therefore, SmallSats are more effective in constellation formation because it helps them overcome their limitation of less swath area and less resolution of sensors. Their short-term development period allows them to be more flexible, responsive to advancements specially in remote sensing and earth observation area. In today's date, earth observation missions are critical for mapping, area statistics, surveying and many more. With the increase in natural and man-made disasters around the world, first priority is live updates, coverage of the disaster struck area so that the disaster management agencies can easily access the area for support and rescue purposes. In case of earth observation satellites, providing live coverage from satellite-based observation sensors requires an insane number of satellites to minimize the revisit period so as to meet the required time period for live feed. Instead of live coverage, the primary aim of the earth observation satellite is to provide the data with the minimum latency period. Hence, the satellite constellation is used in this scenario. Satellites are placed in orbit with the purpose of maximizing the coverage area meanwhile not expensing on the revisit period of the satellite.[1][2][3]–[5]

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1.1 Satellite System and Earth Observation Missions

The satellite missions are always carried out with the help of satellite system. Satellite system refers to the complete network of satellite constellation, ground stations and response agencies. Satellite systems needs to be interoperable for easy handling functionality and modular in design so that in case, update is required for new technology, the system can be updated in short amount of period and with minimum cost. The Earth observation satellite or satellite systems are the class of satellite that are used for the purpose of observation of a portion of earth for various scientific and economic purposes. The process is also called remote sensing. The missions generally are equipped with the sensors to survey the patch of earth under their swath and transmit the data to the allocated ground station for the further data processing and evaluation. This data is further used for the required purposes ranging from, environmental monitoring, meteorology, map making, etc. In case of earth observation, Landsat is the most advanced earth observation satellite system deployed presently. It uses high resolution SAR sensors for earth observation and each satellite of the system weighs nearly 1.5 tonnes. The full satellite system comprises of 2 active satellites with another coming up in 2023, but building large satellites requires large amount of capital investments and with time and upgrade in technologies, the cost will consistently rise up. This calls for more economical solution where one can not only utilize satellites for earth observation but also test new updates in earth observation sensors and technologies at a relatively low budget.

Planning an orbit for these missions are still a challenge for the mission control till date. Planning of proper Keplerian orbital parameters namely, Length of semi major axis, eccentricity, inclination, longitude of ascending node, is utmost necessity as it may affect the swath area or may miss the target region by minor variations. This paper addresses an effective satellite constellation which targets to maximize the coverage area and with minimum revisit period. The satellite constellation is designed for disaster management purposes primarily targeting specifically densely populated areas which are most affected by the disasters. Second consideration taken for the satellite constellation is that it is specifically designed for SmallSat platforms which generally weigh between 50 to 200 kilograms.[1], [6]

1.2 Disaster Area Review

For the selection of the optimal orbit inclination for earth observation, it is necessary to obtain data on the location of the most occurrences of disasters in correspondence to the densely populated areas. Full scale study was conducted regarding nature and frequency of disaster occurrence, loss of life and property. Over the year records of different disaster occurrence in relation to the populated areas is represented as a heat map in the following figure.

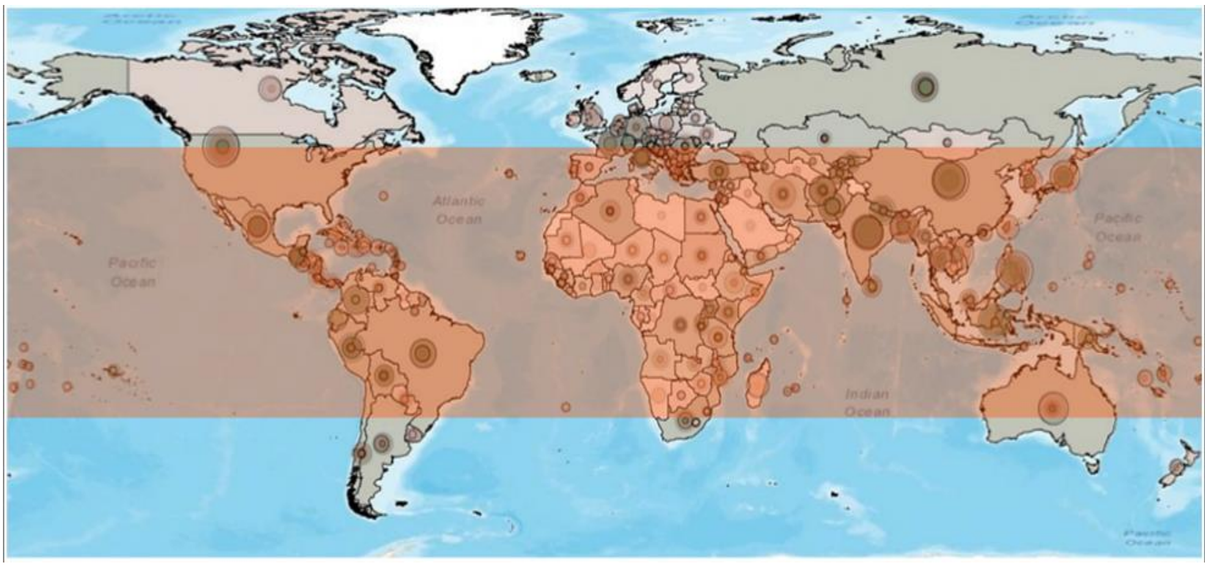

Figure 1: Common disaster scale represented for each country with respect to population

From the study of the heatmap given above, it is clear that most of the disasters occur within the area enclosed by the tropic lines. Therefore, to be more accurate most of the disaster affecting the densely populated areas are present between the tropic of Cancer and tropic of Capricorn and after that in the tropical regions. Accurate inclination of the

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orbit is selected to cover the maximum area without compromising on the revisit period of the satellite as well as the repeat cycle of the constellation. Therefore, while selecting the orbit inclination and parameters, this serve as one of the conditions which is considered as the effective area to be observed.

2. Orbit Selection

The objective of the paper is to design an earth observation satellite constellation with the least possible revisit time period and maximize the coverage area for the equatorial region. Although the revisit time period can be decreased with the increase in number of satellites but financial feasibility is also to be considered while designing the satellite constellation otherwise it defeats the basic criteria of going with the SmallSats instead of large satellites, hence orbit should be selected critically. Therefore, for the same purpose, a trade-off study was done between all types of orbit for different parameters to maximize the effectiveness of the constellation. The trade-off study is shown in Table 1. The parameters considered in the trade study are in reference to the effective area considered earlier in section 1.2.[7]–[9]

Table 1: Orbit Selection Trade Study

Types of Orbit **Parameters**	**Polar**	**Inclined**	**Sun Synchronous**	**Geo Synchronous**	**Elliptical**
Revisit Time Period	0	1	0	-1	-1
Eclipse Time	0	0	1	-1	0
Orbital Perturbation	0	-1	-1	0	-1
Coverage Area per Orbit	0	0	-1	1	0
Satellite Life	0	1	0	-1	-1
Thermal Fluctuations	0	1	-1	1	0
Total Merits	**0**	**2**	**-2**	**-1**	**-3**

Therefore, as it is clear from the table above, Inclined orbit is best suited for the satellite constellation considering the effective area that is to be monitored.

2.1 Inclination Determination

The orbit altitude and inclination of the satellite are selected considering the parameters mentioned in the trade study. Main focus is to reduce the revisit time period of the satellite and to maximize the coverage area of the considered effective area. Secondary focus was on the sun illumination time. It is necessary that the satellite has enough sun illumination time to generate the required amount of power so as to maintain the operation of the payload unit. Generally, for earth observation satellite, close and nearly circular orbit is considered. The shape of the orbit is affected by the following factors:

- Eccentricity of the orbit, e
- Inclination of the orbit, i
- Location of Ascending Node, Ω
- Argument of Perigee, ω

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As the satellites to be used in the satellite constellation have express purpose of earth observation with an objective to maximize area coverage and revisit time period. As we are selecting an inclined polar orbit, maintaining circular shape of the orbit is necessary as earth observation satellite generally follow a nearly circular orbit. Also, as we know that the earth is not spherical symmetrical in shape, therefore the extra mass at equator relative to poles creates a torque on the satellite about the centre of Earth, rotating the plane of the orbit about the polar axis. This results in the secular change in the location of the ascending node known as nodal regression. The regression rate of the orbital plane, $\Omega^{\&}$ depends mainly on altitude and inclination of the satellite:

$$\Omega^{\&} = -\frac{3}{2} J_2 \frac{R^2}{a^2(1-e^2)^2} ncosi \tag{1}$$

J_2 : Coefficient of Earth Oblateness

R : Equatorial radius of Earth

n : The angular speed of circular orbit

μ : The gravitational parameter of the Earth

The nodal regression causes change in argument of perigee which is an undesirable change for an earth observation satellite, as it tends to change the altitude of the satellite with each orbit. Therefore, to avoid nodal regression and to maintain the satellite in a nearly circular orbit, considering equation (1) following values were taken constant as:

Table 2: Orbit Constant Value Assumptions

Argument of Perigee	± 90°
sin (ω)	0
ω_e (angular speed of Earth)	0.004178°/s

To maximize the coverage area of the entire tropical and equatorial region per orbit of the satellite, the inclination of the satellite is considered near to the tropic lines with their limits extending to the pole regions. Running satellite track simulation in SaVoir Taitus software the inclination of the orbit was set at 45°.[1], [2], [9], [10]

2.2 Orbit Altitude Determination

The optimal altitude for most of the earth observation satellite varies from 400 to 700 kilometres range. The higher the altitude of the satellite the more area in covers but this works inversely in relation to the resolution of the sensor. Small sensors do not have high resolution hence orbit should not be taken too high so as to jeopardize the working of the sensor. At the given altitude range, the main limiting factors that affect the life and efficiency of the mission is the revisit frequency of the satellite. The number of orbits per day (Q) influences the ground tracks of the satellite. The number of orbits per day is measured by the formula:

$$Q = \frac{86400}{2\pi\sqrt{\frac{(R_e+h)}{Gm_E}}} \tag{2}$$

Therefore, using the above-mentioned formula, the values are tabulated in Table 3.

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Table 3: Number of Orbits per Day vs. Altitude

Q	h (km)
13	1256.395
14	888.251
15	560.25
16	265.25
17	6.095

As the most acceptable altitude for earth observation satellite is limited from 400 to 700 km, therefore the number of orbits per day is from 14 to 15. The number of orbits per day narrows the orbital altitude range but the altitude cannot be selected with this data. The secondary parameters that decides the altitude of the satellite is the required swath area of the satellite and the number of repeat cycles. As the paper only addresses the satellite constellation design and SmallSat Platforms, the payload will change on a case by case basis resulting in change in the pointing angle of the sensor. Hence for the constellation design the coverage cone of the satellite is considered.

2.3 Satellite Coverage and Revisit Period

For the earth observation satellite, a general observation angle of the coverage cone is taken to be 19 degrees and the footprint of the satellite is considered rectangular with a swath width of 200 kilometres. The assumptions considered are taken in reference to the minimum swath that can be covered by sensors today. The simulation was done using SaVoir Taitus for minimum repeat cycle in the given altitude range at which we can achieve the maximum coverage area in minimum amount of time. The orbit was tested on a particular area of interest which was selected over the south-east Asiatic region having radius of 1002 kilometres. The repeat cycles were tested on this particular region. The observations taken from the simulation are mentioned in the table 4.

Table 4: Repeat Cycle and their coverage rates

Repeat Cycle (Days)	Height (km)	AOI Coverage Area
10	604.3	100%
9	624.6	91.23%
8	658.9	83.04%
7	686.4	76.08%

From the results, 10 days repeat cycle with satellite altitude of 600 km was selected. The effective swath of the SAR antenna can be calculated as follows:

$$W = \alpha * h \tag{3}$$

α : Pointing angle of the Stereo-SAT

W : Swath width of the SAR antenna

The selected altitude of the Stereo-SAT is 604.3 km and the pointing angle is 19^{o} (0.3309 rad). Therefore, using formula (3) we get an effective swath width of:

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$$W = 0.3309 * 604.3$$

$$W = 200\ km$$

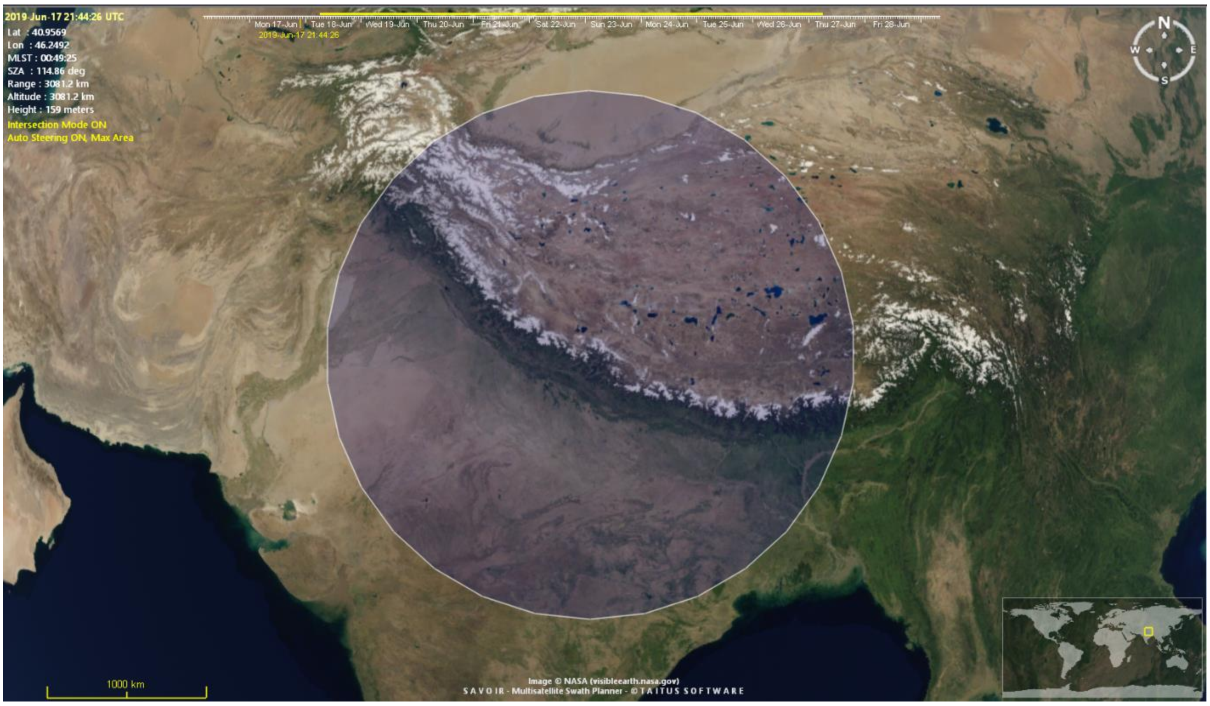

Figure 2: Area of Interest (AOI) considered over the South-east Asiatic Region

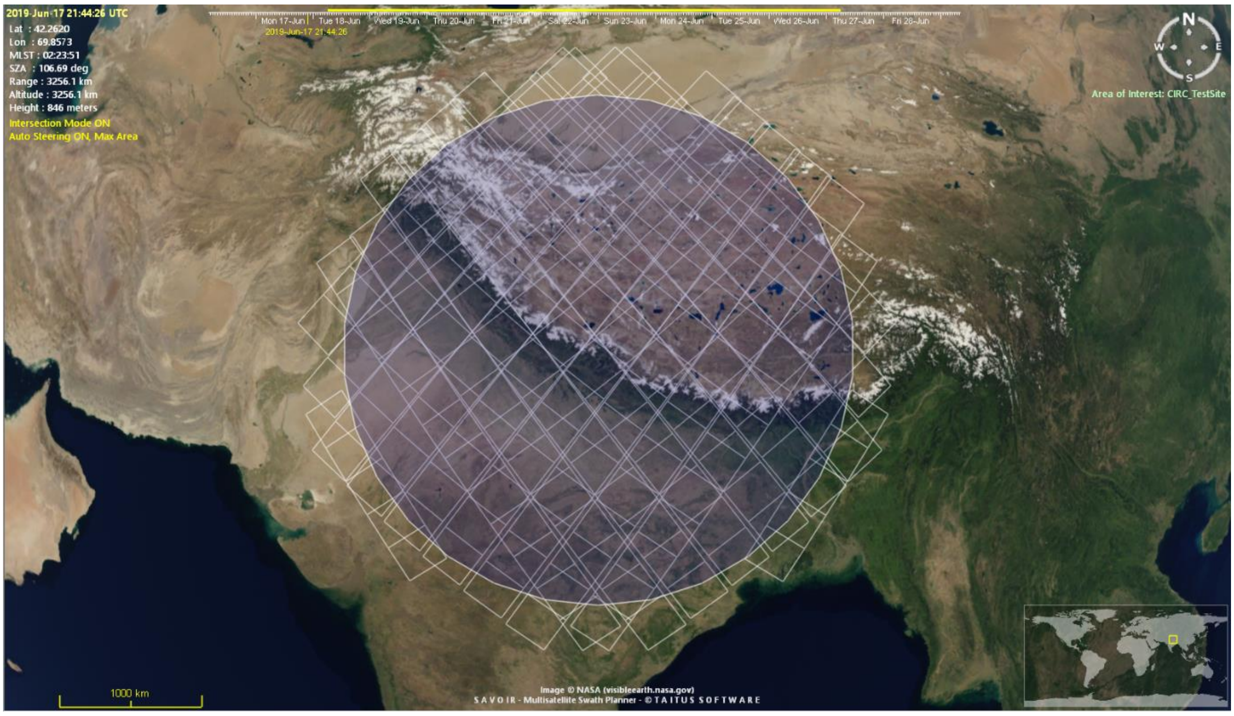

Figure 3: The Swath coverage simulated using SaVoir Taitus Software over the AOI for optimal Repeat Cycle

The effective swath considered for the satellite is 200 kilometres. The effective repeat cycle simulated in Taitus SaVoir is 10 days for a given altitude of 600 kilometres. The data taken from table 1 contradicts the results because it does not

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consider the orbit inclination. The repeat cycles consider both the ascending and descending passes of the satellite orbit. Taking all the options in account for altitude and inclination, the best repeat cycle was taken at 10 days. Therefore, the parameters were tested in SaVoir Taitus for the orbit details which are mentioned in the table 5. The 2-D and 3-D orbital track for an individual satellite is shown in the figures below.

Table 5: Orbital Parameters of constellation satellite

Type of Orbit	Inclined Orbit
Semi-Major Axis	6981.02 km
Eccentricity	0.0007
Inclination	55.018 deg.
Arg. Perigee	0.874 deg.
Mean Anomaly	359.194 deg.
Repeat Cycle	10 days 4 hours
Cycle Length	147
Orbital Time Period	96.573 min
No. of Orbits per day	14.91
Orbit Height (average)	604.32 km

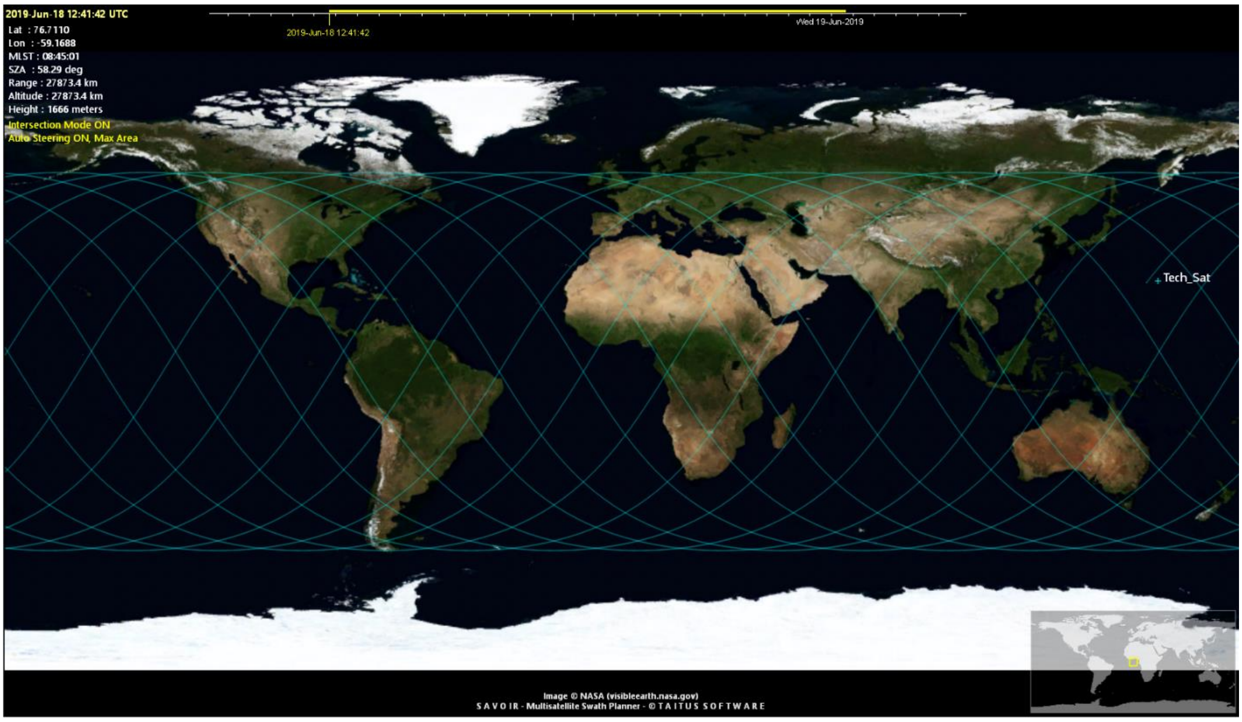

Figure 4: Two-dimensional orbital track of a Single Satellite

To validate the results for selected parameters, the values were run against orbital parameters of Terra-SAR X satellite using Taitus software only, and the result was a stable orbit. Running the complete simulation in SaVoir, the effective revisit time period of the satellite was found to be 10 days and 4 hours which is 244 hours. This is the most optimal configuration of orbit for single satellite providing effective coverage of the disaster prone and densely populated areas with minimum revisit time period, although it is to be reduced further with the help of effective constellation design.

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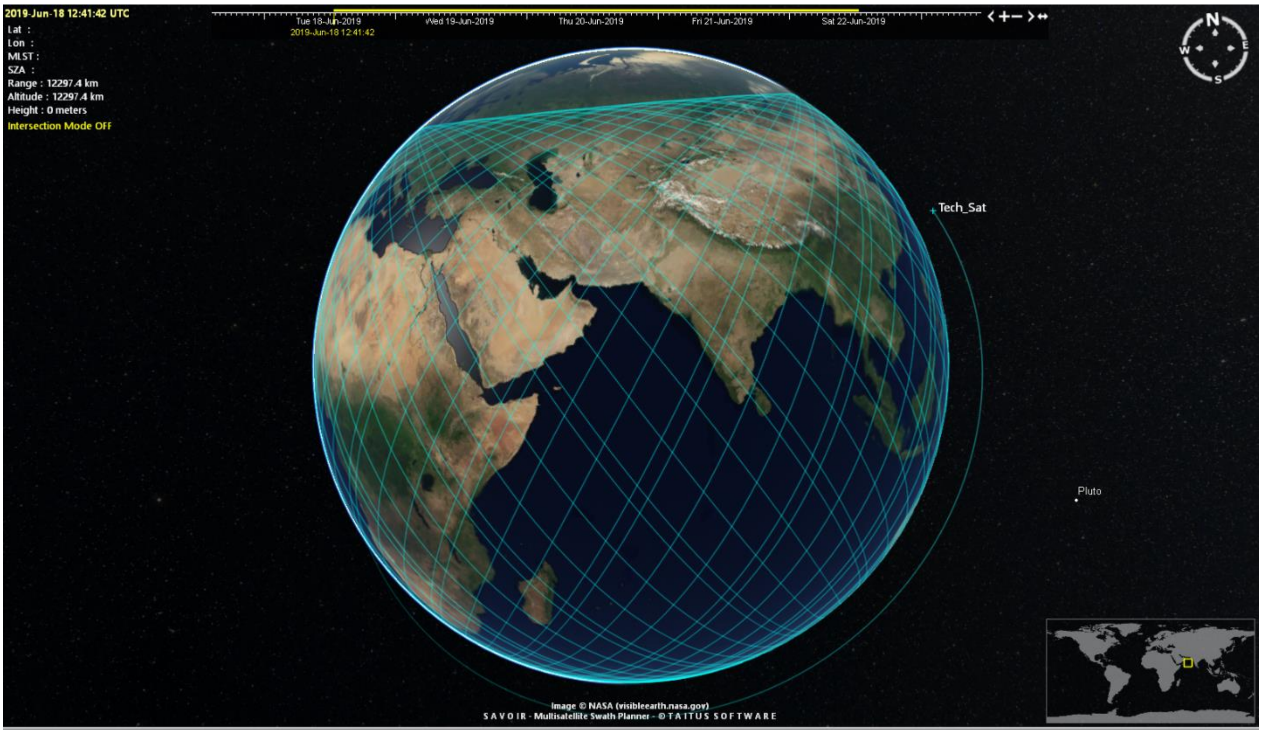

Figure 5: Satellite Orbital Track over 3D google earth using SaVoir Taitus

3. Satellite Constellation

Constellation are designed to reduce the revisit time periods of the satellites, effective uplink and downlink communication and to increase area coverage rates. The best example present of the satellite constellation is the Starlink Satellite System designed by SpaceX to provide internet even at the remote places of the earth. The entire satellite system comprises of 12,000 satellites which are connected via intersatellite link to each other. Although the starlink system is very complex consisting of several orbital shells and numerous orbital planes. But, in our case the constellation is to be designed for an earth observation mission and the target is that common sensor is being used in all the satellite platforms therefore the system will have only orbital shell. The basic types of satellite constellation taken for the reference are as follows:

1. Walker Star Constellation
2. Ballard Rosette: Walker Delta Constellation
3. Teledesic Constellation
4. Disaster Monitoring Constellation

As mentioned above, there is reference orbit specifically designed for the disaster monitoring but they are effective only for satellite having full polar orbit parameters and the constellation design requires them to be accurate on the pointing angle of the sensors for the effective design of the orbits whereas, to design a just constellation with general coverage area of the satellite in consideration, this particular has many shortcomings. The different types of constellation are represented on altitude scale in the figure 6. Considering the inclined orbit, the reference constellation taken for the satellite system design is Ballard Rosette: Walker Delta Constellation. This satellite constellation reference has been taken from the works of A.H. Ballard. In this type of configuration, the satellite constellation is arranged in a pattern having rosette or flower like orbital patterns. The best results are obtained with this type of configuration when 5 to 20 satellites are used. The data is based on the already evaluated and identified results. Most of the configurations involve placing the satellite in N number of orbital planes depending on the ease of the launch and deploy ability on an inclined orbit. This not helps in reducing the repeat cycle but also helps in decreasing the rate of revisit time period per orbit if multiple number of satellites are placed in a single orbital plane. Coverage properties of these constellations are analysed in terms of the largest possible great circle range between an observer anywhere on the Earth's surface and the nearest subsatellite point.[1], [2], [6], [9], [10]

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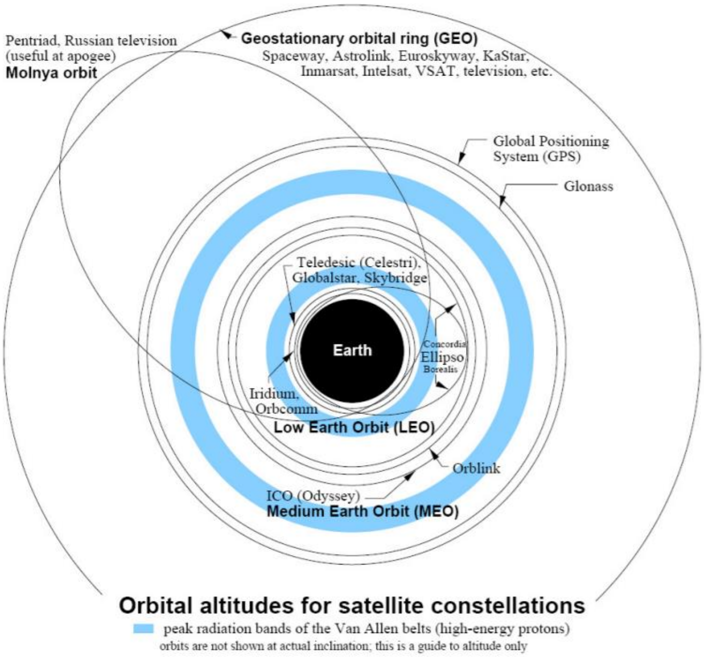

Figure 6: Graphical Representation of orbital altitudes for satellite constellation

When evaluated in this manner, coverage properties are invariant with deployment altitude[11]. Therefore, constellation was tested for different number of satellites with distribution over different orbital planes and the repeat cycle was tested over the same Area of Interest as it was considered earlier when testing for single satellite. The results from the simulation are tabulated in the table below:

Table 6: Satellite Constellation Simulation Observation in SaVoir Taitus

Number of Satellites	Orbital Planes	Number of Satellites per Orbital Plane	Repeat Cycle (hours)
2	1	2	122
3	3	1	81.3
5	5	1	48.8
6	6	1	40.7
6	3	2	40.7
10	5	2	48.8
10	10	1	24.4
20	10	2	48.8
20	20	1	12.2

Therefore, studying the tabulated results, the most effective constellation to reduce the repeat cycle to less than 12 hours, the minimum number of satellites needed for the constellation is 20. The repeat cycle period can be further reduced by increasing the number of satellites in a given orbital plane and then increasing the number of orbital plane, but the effectiveness should be prioritized with minimum number of orbital planes possible because more the orbital planes for a given earth observation mission, it calls for more complex coordinated launch for given orbit. It is also observed that when the number of satellites is increased more than 5, increasing number of satellites per orbit only affects the revisit time period and not the repeat cycle of the constellation as stated by Ballard Increase in orbital planes

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results in decrease in revisit time period of the satellite system. Therefore, final constellation was designed with 20 satellites over 20 orbital planes in Walker Delta Star Constellation.

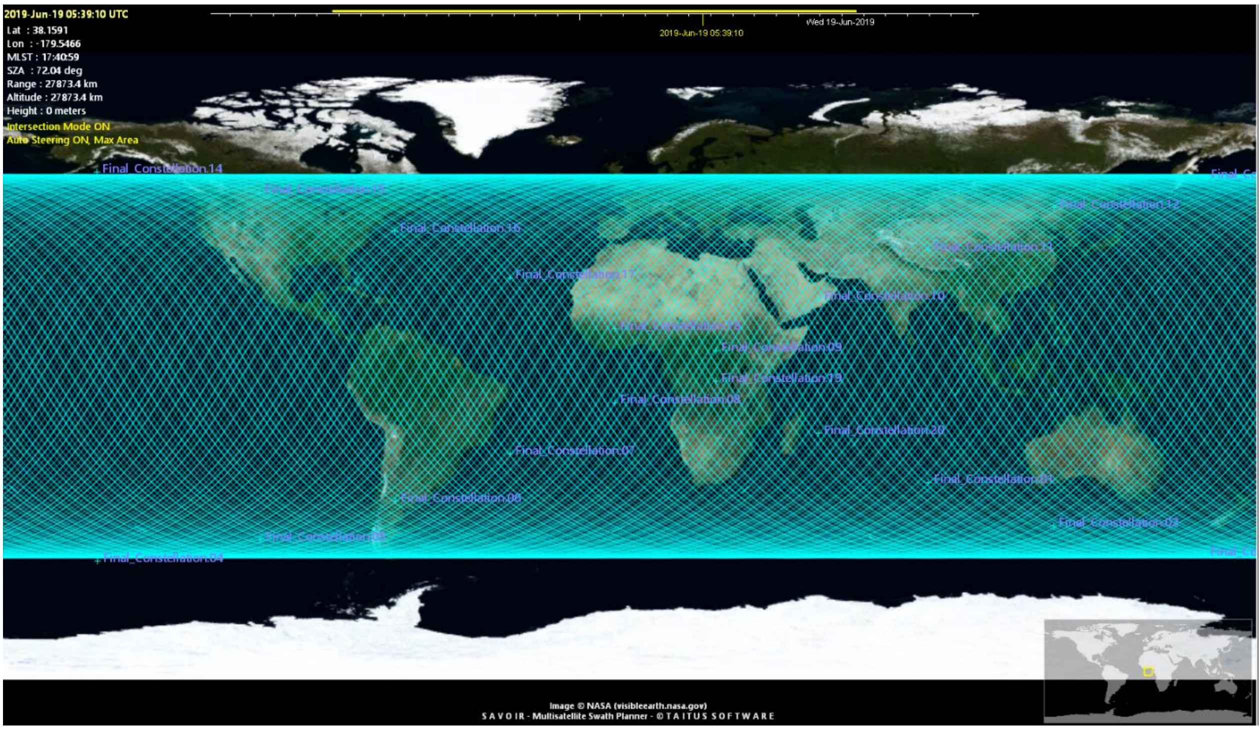

Figure 7: 20 Satellite Ballard: Walker Delta Star Constellation with the orbital tracks

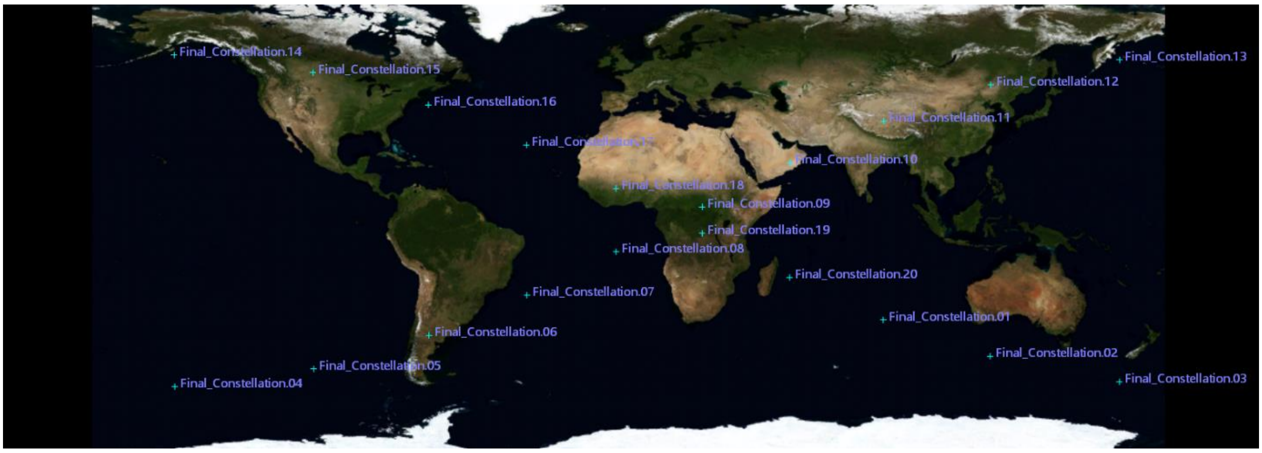

Figure 8: 20 Satellite Ballard: Walker Delta Star Constellation without the orbital tracks

4. SmallSat Platform Review

Among the major classification of various satellites, the classification by mission and mass are the most prominent once. Based on the mass the small satellites or Micro satellites are the class of satellites with the operational launch mass of 50kg to 250kg. The satellites are most widely used for low budget and small tenure missions. Preferentially by smaller company obtaining data for corporate and business use prefer this satellite category as the mass is low and overall cost of launch, deployment and operation is very low and manageable. Due to increase in such requirement various aerospace and space agency have developed the commercial form of the industry and have started manufacturing the satellite platform similar to the CubeSats. In the table given below are some of the options which are available in the small satellite category which are preferred by various customers around the world for LEO, and GEO orbital missions[12][13][2][13].

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Table 7: SmallSat Platform Review

Sl. No.	Name of platforms	Manufacturer	Weight	Payload capacity	Orbital Life
1	Indian Mini Satellite (IMS-1)	ISRO	Up to 100 kg	Up to 30 kg	NA
2	S-50 small satellite platform	SITAEL	Up to 50 kg	Up to 20kg	3 years
3	ALTAIR™ small satellite platform	Millennium Space Systems	Up to 50 kg	Up to 25kg	NA
4	NAUTILUS	UTIAS Space Flight centre	Up to 150 kg	Up to 70kg	5 years
5	SSTL 70	NASA SSTL	Up to 50kg	Up to 10kg	5-7 years
	SSTL 100		100 kg	15-20kg	5-7 years
	SSTL 150		103kg (dry bus mass)	Up to 50kg	5-7 years
	SSTL 150 ESPA		115kg (dry bus mass)	Up to 65kg	7years
6	SN 100	Sierra Nevada Corporation	100kg	116kg	5 years
	SN 200		200kg	155kg	5 years
7	BCP 100	Ball Aerospace and Technology Corporation	Up to 180kg	Up to 70kg	5years
	Rapid III BCP 300		Up to 390kg	Up to 250kg	1 year

5. Conclusion

From the observations and simulation conducted on various configuration of constellations, most effective constellation for earth observation mission is 20 Satellite Walker Delta constellation with each satellite having an inclined orbit of altitude 604 kilometres, providing an effective repeat cycle of 12.2 hours for a given area. The orbit essentially covers all the densely populated areas around the world. The given repeat cycle time period can further be reduced but this will require and exponential increase which requires more capital investment although compared to a full-scale large satellite build, deployment and area coverage, increasing the satellites in the constellation will be more economical. Although the constellation alone is not vital, the communication and interoperability of the satellites plays a major role in the overall efficient working of the satellite system. With an effective communication system and ground station network the latency period of the data transfer can be largely reduced and the satellite system can be effectively used to provide live updates in case of some areas are affected by disaster. Modern manufacturing and fabrication techniques also provide solution to this with the help of the publicly available satellite platforms. Major

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manufacturers provide satellite platforms with communication system, power system and ground station support with payload spacing where the earth observations sensors can be fitted. This cuts down on manufacturing costs and time period by numerous levels. The platforms are easy to update and deploy which also helps in testing new equipment on them.

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