Remote Sensing Satellite Constellation Design Based on Repeat Ground Track Orbits Properties

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Abstract. The study addresses the problem of Earth remote sensing discontinuous coverage satellite constellation design. An approach is developed to calculate the minimum number of LEO satellites to ensure periodic coverage of entire region of interest on Earth for a given telescope characteristics. It utilizes ground track properties of repeat ground track LEO orbits.

Introduction

Earth remote sensing is one of the key space applications. Remote sensing missions in most cases provide discontinuous Earth coverage and can require single satellite or multiple satellites constellation depending on mission requirements. Remote sensing missions are characterized by sensor ground sample distance (GSD) defining image resolution, instrument swath width S_w, and by various coverage Figures of Merits (FOMs) such as revisit time and response time statistics and percent coverage. Remote sensing space system design necessitates various considerations including coverage geometry, orbit and constellation design, station-keeping, data downlink and others.

The study addresses the Earth remote sensing constellation design problem given the sensor parameters, required image quality, and coverage FOMs. To design a satellite orbit and corresponding orbital configuration in a way guaranteeing certain coverage properties, two general approach can used: multi-objective optimization [1] and analytical consideration of satellite ground track [2]. The paper studies the problem of remote satellite constellation design using ground track properties of repeat ground track (RGT) orbits. An RGT orbit has commensurability of its nodal period T^n_{sat} with nodal period of the Earth self-rotation $T^n_{\oplus}$ and is defined by a number of satellite revolutions to repeat its ground track R within D nodal days. Moreover, taking into account optical observation limitations to daytime imaging we restrict orbits to sun-synchronous to avoid observation of unlit territories.

Problem Statement. Given telescope angular resolution θ_r, find RGT SSO circular orbit radius R and corresponding minimum number of satellites n_{sats} to provide coverage of an area of interest (AOI) with a certain revisit time T_{rev} and a required image quality as per National Image Interpretability Rating Scales NIIRS.

1. Sensor Geometry

Let's consider a constellation containing optical telescopes-equipped satellites. A telescope is defined by its angular resolution θ_r and field of view θ_{fov} for coverage geometry analysis. Figure 1, a) depicts side pointing beam geometry required to calculate GSD for different look angles θ. Look angle defines field of regard (FOR) of a satellite, i.e. a potential area on Earth that can be observed by a steerable sensor and a corresponding sensor swath width $S_w = 2\beta_c$. The relation of ground sample resolution (GSD) with orbit radius R and maximum look angle θ at which a telescope can perform observation is described as follows

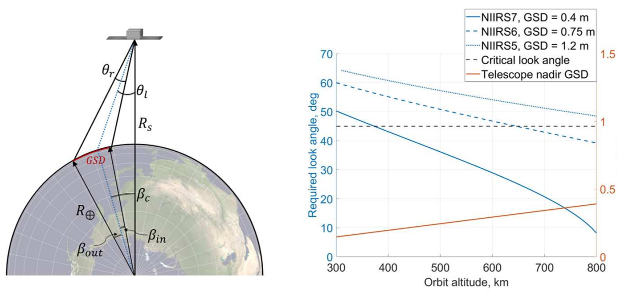
$$GSD = (\beta_{out} + \beta_{in}) \cdot R_{\oplus}, \tag{1}$$

$$\beta_{in} = \beta_c - \frac{\pi}{2} - (\theta_l - \frac{\theta_r}{2}) - \arccos(\frac{R_s}{R_{\oplus}}\sin(\theta_l - \frac{\theta_r}{2})),$$

$$\beta_{out} = \frac{\pi}{2} - (\theta_l + \frac{\theta_r}{2}) - \arccos(\frac{R_s}{R_{\oplus}}\sin(\theta_l + \frac{\theta_r}{2})) - \beta_c,$$

$$\beta_c = \frac{\pi}{2} - \theta_l - \arccos(\frac{R_s}{R_{\oplus}} sin(\theta_l)).$$

Figure 1, b) shows relations of: nadir pointing GSD for different orbit altitudes, and satellite look angle yielding different image qualities according to the NIIRS classes for different orbit altitudes.



(a) (b)

FIGURE 1. a) Sensor geometry, b) Nadir GSD(h) & Required look angle $\theta(h)$ to achieve different GSD or NIIRS classes.

2. Satellite Ground Track

Satellite ground track is a locus of sub-satellite points or points on the Earth surface having the same unit vector $\mathbf{e}^E_{sat}$ as the satellite position vector $\mathbf{R}^E_{sat}$ given in Earth-Centered Earth-Fixed (ECEF) frame. It is common to consider 2D ground track plot (see Fig. 2, a)) where satellite location is defined by a corresponding spherical coordinates or latitude ϕ, and longitude λ.

Figure 2, a) depicts 2D ground track of an RGT SSO orbit that performs 29 revolutions within 2 nodal days. An important parameter for Earth observation mission design is so called fundamental shift S_F. It shows how satellite ground track shifts westward (for LEO satellites) after one nodal period and is calculated as follows

$$S_F = (\omega_\oplus - \dot{\Omega}) \cdot T^n_{sat} = 2\pi \cdot \frac{1}{Q}, \tag{2}$$

where $\omega_\oplus$ is Earth self rotation angular velocity, $\dot{\Omega}$ is secular precession rate of satellite RAAN, $Q = R/D$ is orbit repeating factor describing number of satellite revolutions within one day. It should be noted that Eq. 2 represents fundamental interval at equator while it changes depending on latitude. $S_F(\phi)$ can be found using equations for spherical triangles. Figure 2, b) depicts $S_F(\phi)$ curves for orbits of different altitudes.

Another important property is the maximum latitude of satellite ground track ϕ_{max} that is defined by satellite inclination i is as follows:

$$sin(\phi_{max}) = sin(i). \tag{3}$$

It it crucial parameter to ensure coverage of entire area of interest.

3. Constellation Design Approach

The main objective of this study is to identify the minimum required number of satellites n_{sats} to achieve consecutive coverage of all points in a specific region multiple times within a day. Since an optical satellite can only perform imaging during daytime, it has only single opportunity to pass above a certain Earth region within a day for LEO. Therefore, if several access are required, multiple orbital planes should be considered for the satellite constellation.

Let's consider a single plane constellation design yielding a complete coverage of an AOI per day in this study. To get multiple access per day, the configuration of the single plane constellation could be repeated with multiple identical orbital planes shifted by RAAN with respect to each other.

In order to find the required number of satellites n_{sats}, the fundamental shift S_F and swath width S_w at different altitudes h can be considered (refer to Fig. 2, c)). As can be noted from the figure, the swath width S_w of a satellite at LEO with maximum look angle θ of 45° is always smaller than the fundamental shift S_F. Therefore, more than one satellite is needed to ensure the coverage of the entire

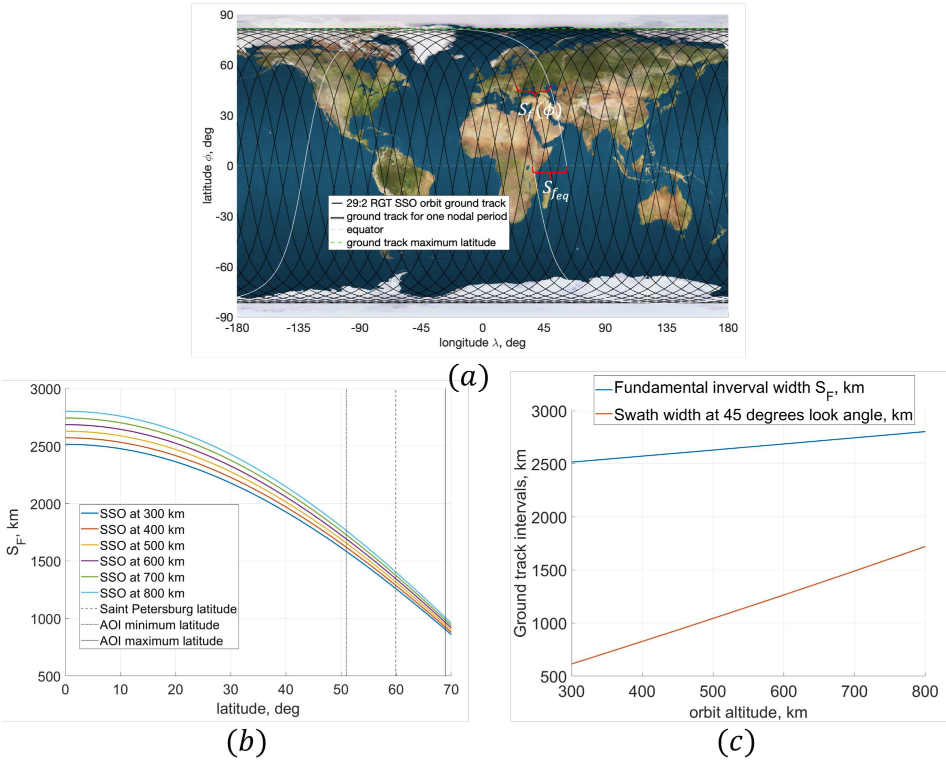


FIGURE 2. a) Ground track Example, b) Fundamental interval S_F versus latitude for sun synchronous orbits of different altitudes, c) Fundamental interval S_F and swath width S_w versus altitude

AOI. The minimum number of satellites to ensure full coverage of the entire area of interest can be found as follows:

$$n_{sats} = \left\lceil \frac{S_F(\phi_{min})}{\tilde{S}_w} \right\rceil, \tag{4}$$

$$\tilde{S}_w = S_w \cdot \frac{1}{\sin(i')}, \tag{5}$$

$$i' = \frac{\sin(i)}{\cos(i) - 1/Q}, \tag{6}$$

where ϕ_{min} is the minimum latitude within an AOI, i' states for apparent inclination.

In order to provide evenly spaced satellites' ground tracks within fundamental interval S_F, the distance between adjacent ground tracks is found as follows

$$\Delta\lambda = \frac{S_F(0)}{n_{sats}},$$

while satellites can pursue the ground track by either RAAN separation or MA separation. The former requires satellite at different planes, i.e. different RAANs, while the latter can be made using single plane. Thus, to yield ground track shift of $\Delta\lambda$ either of the following conditions shall be met:

$$\begin{cases} \Delta\Omega = \Delta\lambda, \\ \Delta MA = \Delta\lambda \cdot Q. \end{cases} \tag{7}$$

4. Constellation Design Example

Let's consider a circumference of Saint Petersburg (latitude $\phi = 59.94°$, longitude $\lambda = 30.31°$) with radius of 1000 km as an area of interest (AOI), yielding minimum latitude $\phi_{min} = 50.95°$. A telescope with diameter $D = 1$ m and angular resolution $\theta_r = 4.88 \cdot 10^{-7}$ rad is considered.

Let's find constellation yielding the entire coverage of the AOI daily with NIIRS 6 (0.75 m GSD) and NIIRS 7 (0.4 m GSD). In this study, 29:2 circular RGT SSO orbit is considered. The orbit altitude is $h = 727.1$ km and inclination $i = 98.27°$.

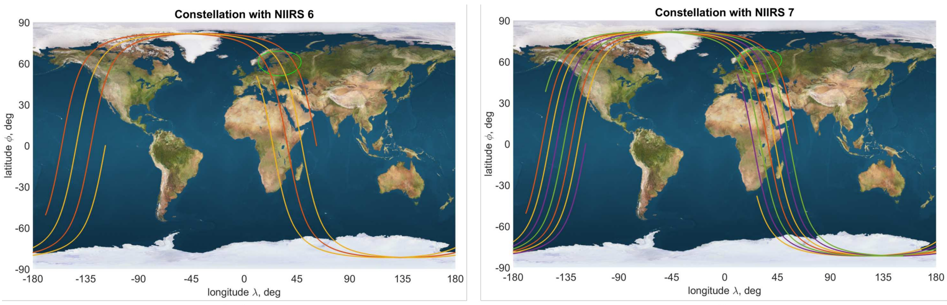
Table 1. Constellation parameters

Parameters	NIIRS6	NIIRS7
Number of satellites	2	4
Swath width S_w, km	1357.8	458.4
Maximum look angle θ, degrees	41.6	17.4
Minimum swathes overlapping, %	35.98	5.19
Mean anomaly separation ΔMA, degrees	180	90

Figures 3 a), b) show ground track of the single-plane satellite constellations guaranteeing daily observation of the entire AOI with image quality scales NIIRS6, and NIIRS7, respectively.

Conclusion

The study developed a method for Earth remote sensing constellation design utilizing satellite ground track properties. A coverage geometry model was introduced relating optical telescope parameters, GSD and swath width S_w, and look angle θ for a given LEO orbit. An approach is developed to define the minimum number of satellites to ensure a periodic imaging of the entire AOI for a given LEO orbit



(a) (b)

FIGURE 3. a) Satellites ground tracks for NIIRS6: 2 satellites per orbital plane to cover AOI. b) Satellites ground tracks for NIIRS7: 4 satellites per orbital plane to cover AOI.

characterised by its ground track fundamental interval S_f and satellite instrument swath width S_w. An example is presented demonstrating the application of the method for constellation design.

References

[1] W. Crossley, E. Williams, *Simulated annealing and genetic algorithm approaches for discontinuous coverage satellite constellation design*, Engineering Optimization, 2000

[2] Ortore Emiliano, Cinelli Marco, Circi Christian, *A ground track-based approach to design satellite constellations*, Aerospace Science and Technology, 2017

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