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Orbit design for an Earth observation satellite in coordination with VNREDSat-1 for minimal combined revisit time over Vietnam

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Abstract: This paper presents a simple approach to define the orbit to coordinate with existing one to form a constellation of satellites with discontinuous coverage and reduced revisit time. This approach is based on analyzing the ground track grid to find possibilities, and choosing the optimal result considering practical constraints such as allowed passes duration, consecutive passes interval. The method is applied for Earth observation system with satellites with narrow field of view of payload, orbiting in Sun-synchronous orbit. The advantage of the method is relatively simple and intuitive. The operational orbit of VNREDSat-1 satellite is used as input data and the above method to calculate the second satellite orbit, temporarily called VN-2. The theoretical results are simulated by using some specialized software such as GMAT (General Mission Analysis Tool), Orbitron and STK (Satellite Tool Kit).
Keywords: Ground-track grid, combined revisit time, satellite constellation, discontinuous coverage

I. INTRODUCTION

VNREDSat-1 satellite is Vietnam's first remote sensing satellite launched into space since May 2013 with its mission of imaging the Earth's surface [[1]]. During the designed life time of 5 years in the Sun synchronous orbit with altitude at about 680km, the satellite has taken and downlinked to the ground station more than 90 thousand scenes with an average number of 40 scenes a day, providing a source of up-to-date high quality remote sensing data contributing significantly to the development of the domestic space technology industry as well as in the fields of economy, national defense and security.

To further enhance the imaging capabilities of the VNREDSat-1 system, adding more satellites to create a satellite constellation is necessary to cut down its revisit time, shorten the gap between acquisitions. The design of satellite constellation is driven by many factors that need to be considered. There is no general pre-emptive rule that can be applied to all situations. The calculated parameters will depend on the specific tasks. Usually the satellite constellation will use the same parameters such as altitude, angle of inclination, eccentricity for all the satellites within. With this similarity, orbital perturbations have similar effects on all the satellites of the constellation so the required maintenance activities are simpler helping the satellites are in longer services [[2]].

There are number of methods that have been developed and widely used in satellite constellation design. Early researches by Walker [[3]],[[4]] yielded the development of symmetrical constellations and their ability to provide continuous coverage. The symmetrical constellation properties for the continuous coverage problem were further inspected by Walker [[5]], Lang [[6]]-[[8]] and others, and being widely known as “Walker constellation”. The main alternative to the symmetrical constellation method called Polar, Non-Symmetric design method, uses the Streets-of-Coverage approach [[9]]-[[11]]. This method uses calculus to determine the solution families as polar orbital constellation with the minimum number of satellites to meet the task so that the calculation speed is much faster than the above method.

These mentioned methods are applied to design satellite constellations with continuous coverage, with rather large number of satellites required. From practical demand as designing Earth observation satellite system using relatively small amount of satellites with narrow swath width, it is not available using those above methods. In this article, the authors present a simple approach based on the analysis of ground track grid with visual advantages to apply to design orbit for satellites capable of coordinating with existing satellite on Sun-synchronous orbit to reduce revisit time. The method was applied to actual case as VNREDSat-1 satellite and simulated by using dedicated tools such as GMAT, Orbitron and STK.

II. MATERIALS AND METHOD

2.1 Orbit characteristics of VNREDSat-1 satellite

2.1.1 Orbit trajectory

The theoretical orbit of VNREDSat-1 satellite is fixed as a Sun-synchronous orbit and the satellite orbits 14 + 18/29 revolutions around the Earth in one day. The average local time calculated at the ascending note is 22h32.

Orbit parameters of VNREDSat-1 satellite are given in the Table 1.

Epoch	2013/04/01 22:32:00.000
Ground track cycle	14 +18/29
Frame	J2000
Semi-major axis (km)	7058.907082
Altitude (at Equator) (km)	680.767
Eccentricity	0.00120705
Inclination (degree)	98.1471783
Right ascension of ascending node (RAAN) (degree)	168.2814491
ω(degree)	90.074794
M(degree)	270.0
Local solar time (ascending node)	22h32
Period (second)	5909.4

Table 1 Reference orbit parameters of VNREDSat-1

2.1.2 Orbit ground track

Satellite ground track is defined by the projection of its orbit onto the surface of the Earth. In case of VNREDSat-1, the satellite visits the same position on the Earth surface every 29 days which is called one cycle. During one cycle, the ground track divides the Earth equator into: 29 days x (14 + 18/29) revolutions/day= 424 equally parts or $360^o/424 = 0{,}85^o$ in longitude. Other key parameters are computed as follows:

Minimum distance at equator between any two tracks within cycle, called minimum interval as in [[12]]:

40.075km (Earth perimeter)/424 parts = 94.52 km

Distance at equator between two consecutive ground tracks or ground track shift [[13]]:

40.075km (Earth perimeter) / (14+18/29) = 2740, 98 km

or equivalent to $360^o/ (14+18/29) = 24{,}62^o$ in longitude

One part of the ground track grid for 29 days of VNREDSat-1 is shown in Figure 1. The date is numbered from 0 to 28

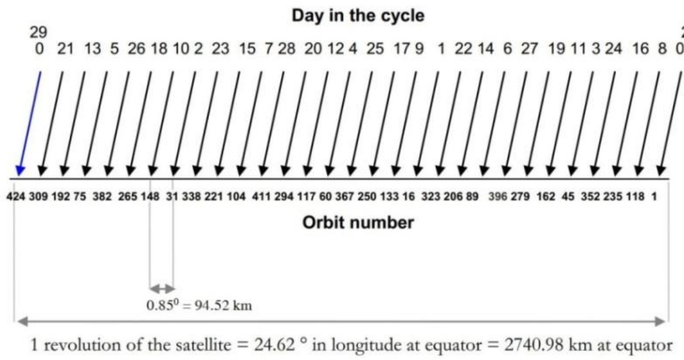
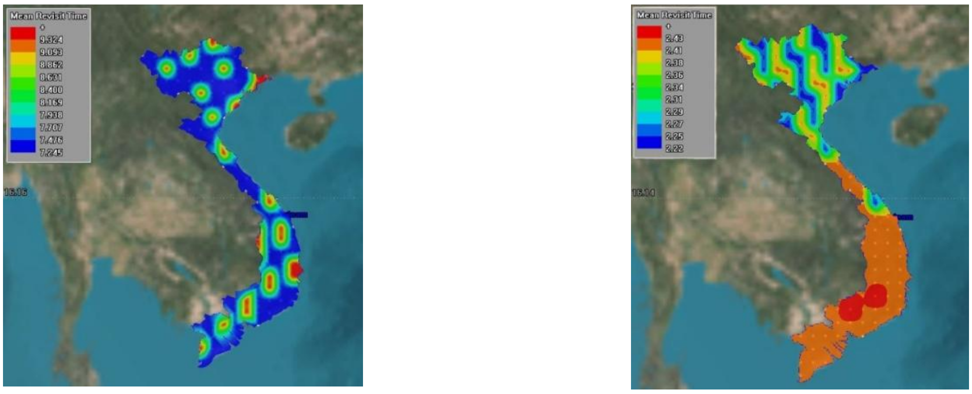


Fig 1.Partly ground track grid of VNREDSat-1 for 29 day cycle.

2.1.3. Revisit time

The selected VNREDSat-1 orbit allows the satellite to reach and capture almost every part of the world no more than 3 days with a roll angle up to 35 degrees and no more than 8 days with an off-nadir angle of lower than 10 degrees. Figure 2 shows the mean revisit period map with 10 and 35-degree roll angles (simulation results by STK software).



(a) (b)

Fig. 2. Mean revisit period of VNREDSat-1 over Vietnam territory: **(a)** Mean revisit time with 10 deg roll; **(b)** Mean revisit time with 35 deg roll

2.2 VN-2 orbital selection

As mentioned in session 2.1.3, the VNREDSat-1 satellite with the Sun synchronous orbit provides the ability to capture almost the entire surface of the Earth with a repeating time of 3 to 8 days depending on the tilt angle. To shorten this repetitive time, a proposed solution is to establish a satellite constellation, in particular adding a satellite in combination with on-orbit VNREDSat-1 satellite. The following will describe the methodology of using the ground track grid of the satellite to compute the revisit time before calculating the orbital parameters for VN-2 satellite.

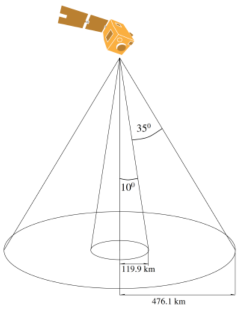


Fig 3. Field of regard of VNREDSat-1 for different tilt angles

It is assumed that the satellite altitude is maintained at around 680km above the Earth surface. The diameter of the area that can be imaged with tilt angle being 10^0 and 35^0 are d = 239.8 km and D =952.3km equals to 2.53 and 10.1 times the minimum interval respectively, the field of view of payload was omitted since it is quite small compared to minimum interval, in the case of VNREDSat-1 it is just 17km Take an example of considering day 1 and day 9 with tilt angle 10^0 , day 15 and day 18 with tilt angle 35^0 for minimum gap of retaking image as shown in Fig 4 below. The ellipses represent the field of regards corresponding to ground tracks on the days that are square-marked. The cross-marked areas are the overlapping regions, which can be retaken image.

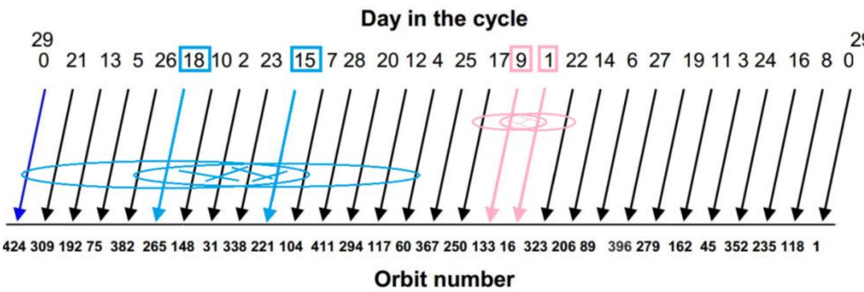


Fig4. Accessible area with tilt angle of 100 and 350

From the diameters of accessible areas with tilt angles are 10^0 and 35^0 as computed above minimal revisit time are 3 days and 8 days, and diameters of overlapping regions are roughly 145.3 km and 479.7 km respectively. More details on calculating swath captures for circular satellite coverage can be found in [[14]].

For repeating Sun-synchronous orbits, their ground track will repeat after a whole number of revolutions R in D nodal days [[12]]. The repeating factor Q represents the number of orbits completed per day and is defined as:

$$Q = \frac{R}{D} = I + \frac{K}{D} \tag{1}$$

In (1), Q can be written as an integer number I plus a fractional part K/D, where K is an integer number which is prime to D, and $0 \le K < D$

In this article, the authors use symbols n,p,q instead of I,K,D. For illustration purpose, the authors use orbit value of VNREDSat-1 as 14 + 18/29.

Initial states are: T_0 corresponds to epoch of D_0 (day) and h_0 (hour) at the longitude of Greenwich, the satellite crosses the first AN of the cycle. Argument of latitude is 0 (the satellite crosses the AN). Longitude of the satellite at T_0 is L_{init} .

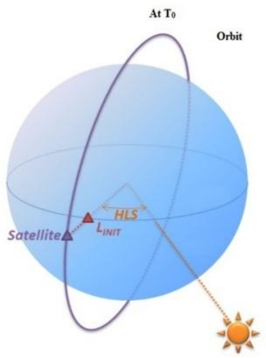


Fig5. Orbit and position of the satellite at T_0

The ground track grid for the first two days of cycle is shown in Figure 6.

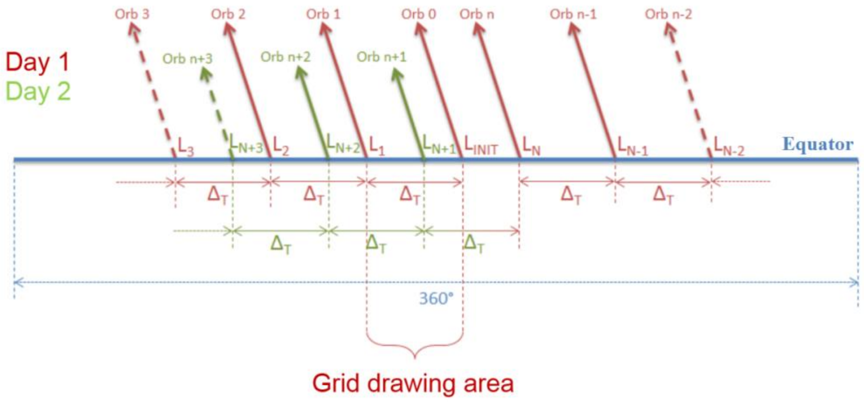


Fig 6 Ground track grid for the first two days

Due to recurring characteristic of the ground track grid, only one part of thatwas analyzed. Other parts can be analyzed in the same way. The distances between ground tracks are calculated as in Figure 7.

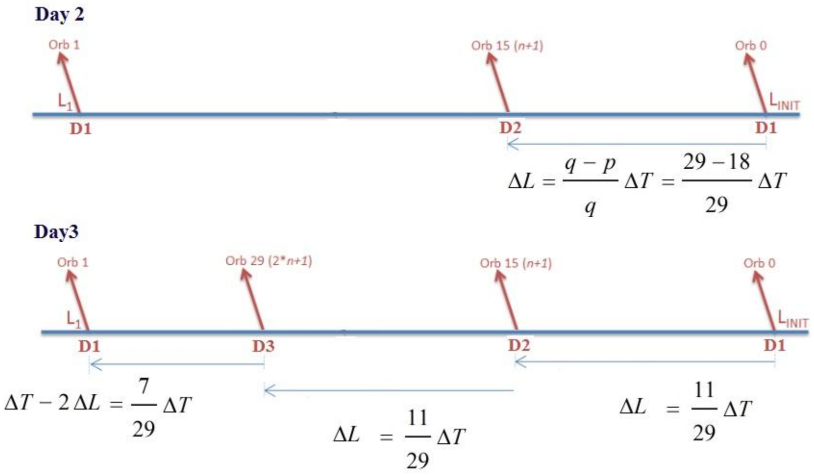


Fig 7 Distance between ground tracks

The ground track grid of day 4 is displayed in Figure 8. Continue the analysis till the last day of the cycle for complete grid as shown in Figure 1.

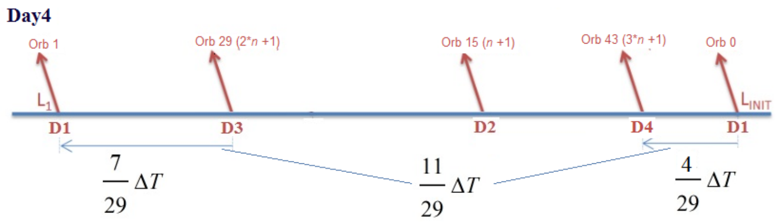


Fig 8 Ground track grid for day 4

For the VN-2 to be able to capture the same area acquired by VNREDSat-1 within the shorter time, it is necessary for the two ground track grid to be very close even overlapping each other. Figure 9 below illustrates a possibility for the task. The ground track grids of two satellites are overlapped, with delay of 1 day.

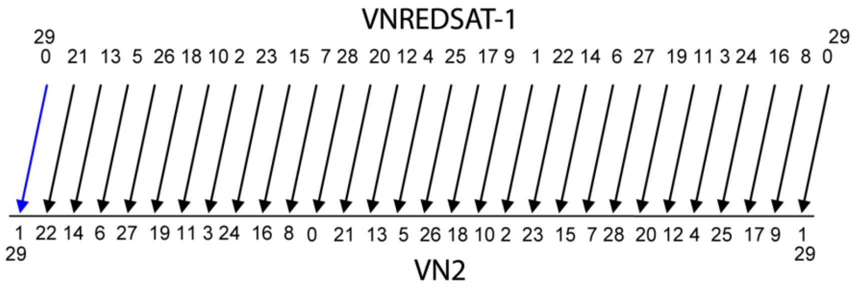


Fig 9 Proposed ground track grid of VN-2 in comparison to VNREDSat-1

In figure 10 to 13, the interested area is arbitrary but small enough to be within two consecutive ground tracks. It is displayed by red color and purple color ellipse while tilt angle is 35^0 and 10^0 respectively. The days which stay in the rectangle are available days in which interested area can be accessed. Blue andgreen rectangle stands for the case of $35^0$and 10^0 tilt angles as for VNREDSat-1. Similarly, the red or rose color rectangle is used for VN-2.

The constellation with same ground track grid and 1 day delay offers the ability to recapture image of interested area after 1 day with both values of tilt angle.

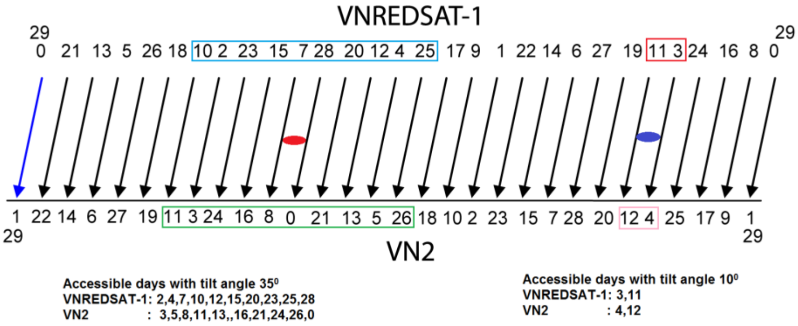


Fig 10 Overlapping ground track, with one day delays

The case of 2 days delay is shown in Figure 11. For any interested area, there are limited days of the cycle which offer 1 day revisit time such as days 1,9,14,17,22,25 of satellite VN2 with tilt angle is 35^0. For 10^0 tilt angle, the gap is 2 days. The cases of 3 and 4 days were shown in Figure 12,13.

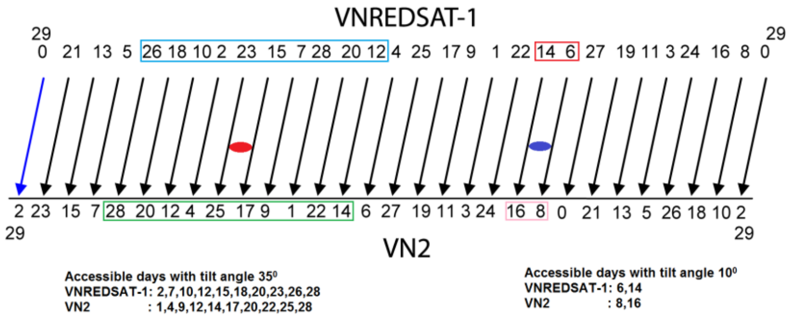


Fig 11 Overlapping ground track, with two days delays

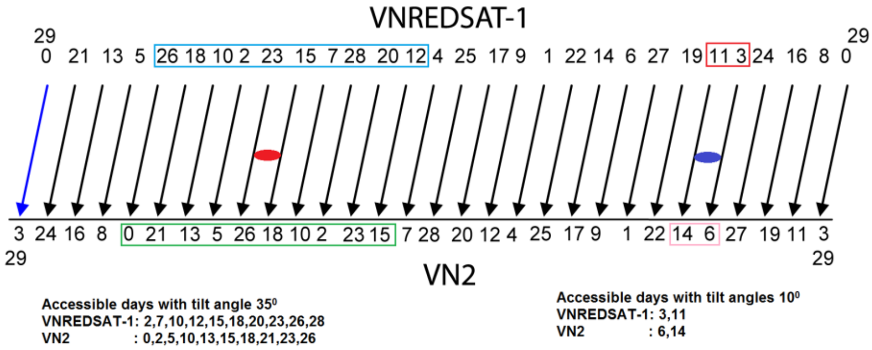


Fig 12 Overlapping ground track, with three days delays

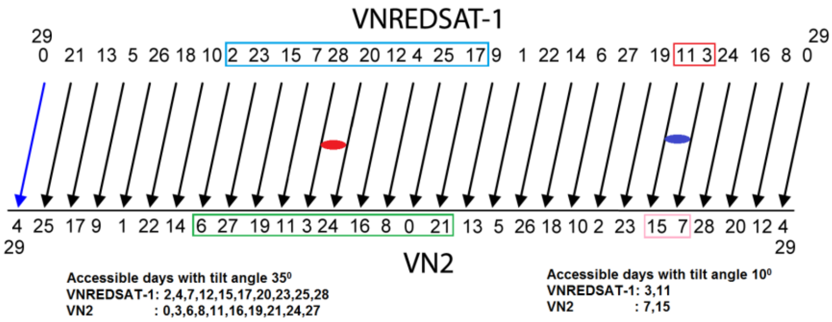


Fig 13 Overlapping ground track, with four days delays

One day delay solution provided the minimum of revisit time for both tilt angles. In other cases the gap are longer.

The following part shows the way to define VN-2 orbit in order to have the same ground track grid with 1 day delay. VN-2 satellite will fly in the Sun synchronous orbit with the same height and shape compared to VNREDSat-1 satellite. Right ascension of the ascending node (RAAN) and the anomaly must satisfy these two conditions:

- ✓ Same local solar time of the ascending node to ensure the same imaging conditions
- ✓ Overlapping of the two ground track grids

The local solar time of ascending node (LST_{AN}) is computed as:

$$LST_{AN} = h_0 + L_{init}\frac{24}{360} \quad (2)$$

Convention for equations later on: the subscripts 1,2 denotes VNREDSat-1 and VN-2 respectively.
The difference in LST AN of two satellites:

$$\Delta LST_{AN} = LST_{AN1} - LST_{AN2} = \left(h_{01} + L_{init1}\frac{24}{360}\right) - \left(h_{02} + L_{init2}\frac{24}{360}\right) \quad (3)$$

With assumption: $L_{init1} \neq L_{init2}$ leads to $h_{01} \neq h_{02}$
Choosing $\Delta LST_{AN} = 0$:

$$(h_{01} - h_{02})\frac{360}{24} = \Delta L_{init} = L_{init2} - L_{init1} \quad (4)$$

From the receptivity of orbit 14 + 18/29 revolutions per day, in the case of Sun-synchronous orbit the duration for the satellite to complete one revolution called nodal period T_{nod} will be

$$T_{nod} = \frac{86400}{14+\frac{18}{29}} = 5909.43 \quad \text{(second)} \quad (5)$$

The distance at equator between two consecutive ground track, R_T is the Earth radius:

$$\theta_T = T_{nod}\omega_T \text{(deg)} \quad (6)$$

$$\text{or } \Delta T = \theta_T R_T (km) \quad (7)$$

With the Earth angular velocity ω_T :

$$\omega_T = 7.27221x10^{-5}(rad/s) = 4.16667x10^{-3}(\deg/s) \quad (8)$$

The distance at equator between longitude of orbit 14th (on first day) and orbit 15th (on second day) equals to:

$$\Delta L = \frac{11}{29}\Delta_T \text{ or } \Delta L = \frac{11}{29}\theta_T$$

To satisfy the second condition above, it is required that the 15th orbit of VN-2 must be coincident with the 1st orbit of VNREDSat-1 (the first and second day is numbered 0,1 in the cycle as shown in Figure 9).

Leading to:

$$\Delta L_{init} = \Delta L \quad (9)$$

Using the orbital parameters of VNREDSat-1 as input, we come up with:

$$\Delta L_{init} = 9.3396^0 \quad (10)$$

The difference in epochs of crossing over first AN of cycle for the two satellite:

$$h_{01} - h_{02} = 9.3396\frac{24}{360} = 0.6226\text{(hour)} = 37.35\text{(minutes)} \quad (11)$$

It means choosing the orbital parameters so that the VN-2 satellite flies on same orbital plane as VNREDSat-1, with 37.35 minutes or 136.55 degrees prior to it. In reality, the VNREDSat-1 system has only one ground control station. It is not allowed to connect both the satellite at the same time. The delay between two satellites as computed offers optimal solution; it provides minimal revisit time which also satisfies the safety requirement.

Satellite	VNREDSat-1	VN-2
Epoch	2018/07/16 04:21:30	2018/07/16 04:21:30
Frame	J2000	J2000
Semi-major axis (km)	7059.2093749	7059.2093749
Eccentricity	0.001250780	0.001250780
i (deg)	98.217460050	98.217460050
RAAN(deg)	269.68294287	269.68294287
ω(deg)	91.727582552	91.727582552
M(deg)	-48.48045331	88.072382651
Local solar time (AN)	22h32	22h32
Nodal period (sec)	5909.4	5909.4

Table 3 Orbit elements of VNREDSat-1 and VN-2

The proposed method is summarized as follow:

- ✓ Constructing of the ground track grid from the existing orbit. Based on the input data as altitude and tilt angle to diagnose the revisit time of it.
- ✓ Choosing the ground track grid of addition satellite to meet the target of reduced revisit time.
- ✓ Computing the orbit of addition satellite considering practical constraints such as allowed passes duration, consecutive passes interval.

III. SIMULATION RESULTS

Table 4 show orbit parameters for the VNREDSat-1 and VN-2, which are used as inputs for simulation and verification.

Satellite	VNREDSat-1	VN-2
Epoch	2018/07/16 04:21:30	2018/07/16 04:21:30
a(km)	7059.2093749	7059.2093749
Eccentricity	0.001250780	0.001250780
Inclination(deg)	98.217460050	98.217460050
RAAN(deg)	269.68294287	269.68294287
ω(deg)	91.727582552	91.727582552
M(deg)	-48.48045331	88.072382651

Table 4 Orbital parameters of VNREDSat-1 and VN-2

GMAT, Orbitron and STK are used as simulation tools and the results are demonstrated as following.

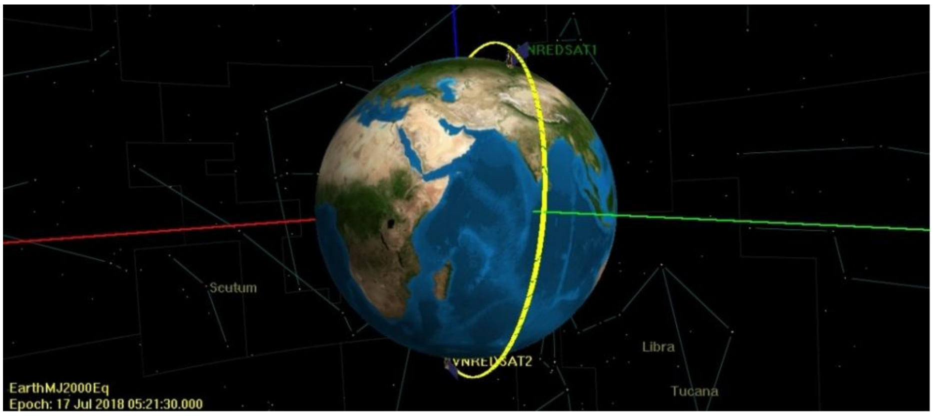


Fig12 3D simulation of VNREDSat-1 and VN-2 on orbits

The two satellites share the same orbital plane, the difference in phasing is 136.55^0, equal to 37.35 minutes.

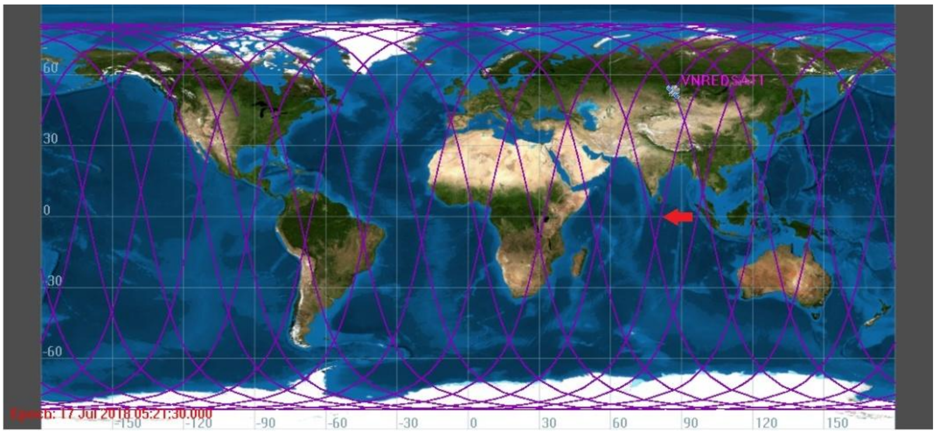


Fig 13 Ground tracks on the first day in cycle of VNREDSat-1

The red arrow indicates the descending node of first orbit, with coordinate are $81{,}0219^0$E, $0{,}0897^0$N.

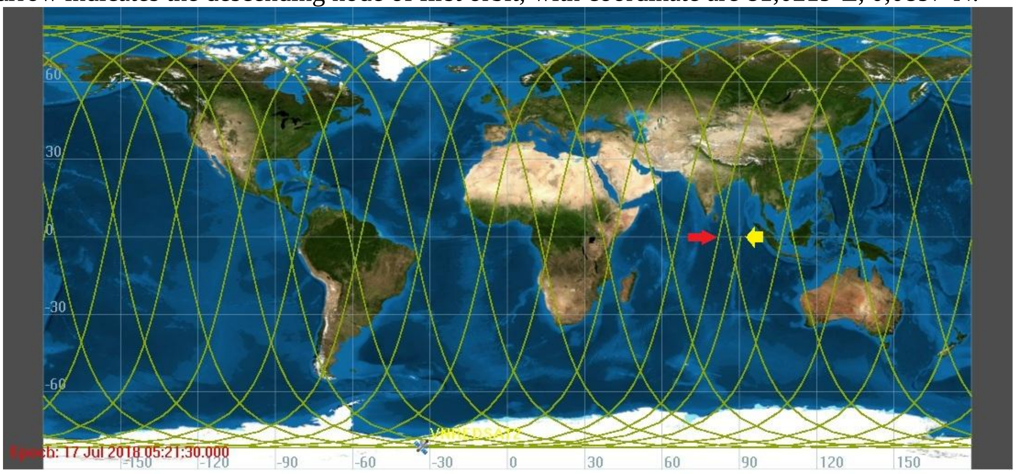


Fig 14 The ground tracks in the first day and first orbit of second day of VN-2

The yellow arrow indicates the descending node of first orbit; the red arrow indicates the first descending node of the second day (orbit 15th) of VN-2. The coordinate for this point are $81{,}0897^0$E, $0{,}3125^0$N.

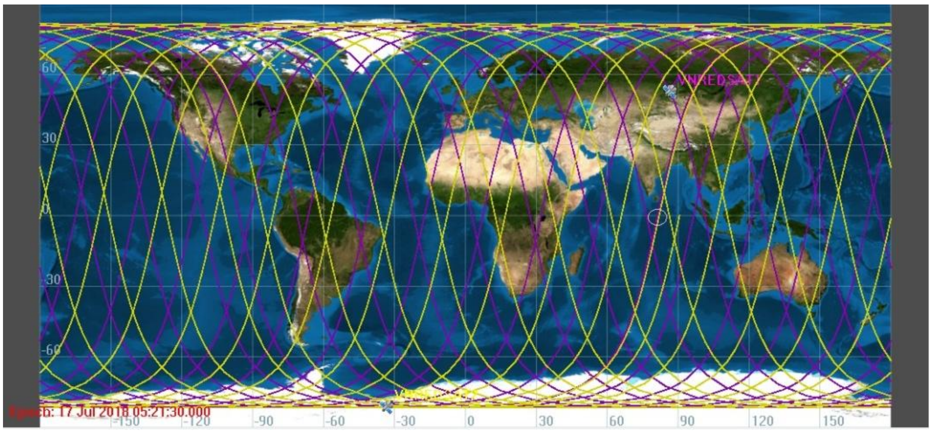
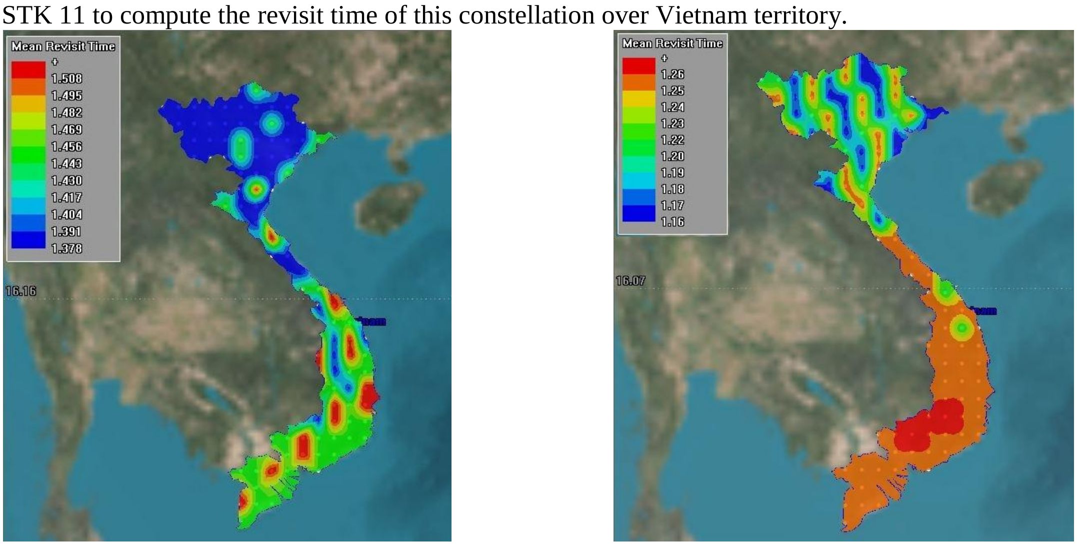


Fig 15 The combination of ground track grid of two satellite

The ground track of these two satellites starts to be coincident at the 15th orbit of VN-2.
Using STK 11 to compute the revisit time of this constellation over Vietnam territory.



(a) (b)

Fig 16 Mean revisit period of the constellation over Vietnam territory:
(a) Mean revisit time 10 deg roll; (b) Mean revisit time 35 deg roll

From the calculated results and ground track grid simulated, it is proved that the computation satisfy the requirements.

IV. CONCLUSIONS

The outcome show the capability in system design for an Earth Observation system, especially in mission analysis method to reduce the top requirement of revisit time over Vietnam territory.The designed virtual constelaltion of VNREDSt-1 and VN-2 guarantee the average revisit time over Vietnam territoty of around 1 day with satellite agility of 35^{o} off-pointing capability, meanwhile the mean revisit time of the VNREDSat-1 alone is 3 days. That means the proposed constellation shall double the imaging capability over Vietnam compared to single satellite. Being designed to offer reduced repeat time imaging over Vietnam, VN-2 and VNREDSat-1 shall increase the temporal resolution for the areas of interest of the country, which is of important factor for observing and monitoring applications.

ACKNOWLEDGEMENTS

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