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Research Article

A Novel Technique to Compute the Revisit Time of Satellites and Its Application in Remote Sensing Satellite Optimization Design

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This paper proposes a novel technique to compute the revisit time of satellites within repeat ground tracks. Different from the repeat cycle which only depends on the orbit, the revisit time is relevant to the payload of the satellite as well, such as the tilt angle and swath width. The technique is discussed using the Bezout equation and takes the gravitational second zonal harmonic into consideration. The concept of subcycles is defined in a general way and the general concept of "small" offset is replaced by a multiple of the minimum interval on equator when analyzing the revisit time of remote sensing satellites. This technique requires simple calculations with high efficiency. At last, this technique is used to design remote sensing satellites with desired revisit time and minimum tilt angle. When the side-lap, the range of altitude, and desired revisit time are determined, a lot of orbit solutions which meet the mission requirements will be obtained fast. Among all solutions, designers can quickly find out the optimal orbits. Through various case studies, the calculation technique is successfully demonstrated.

1. Introduction

Satellite missions devoted to the observation of the Earth as well as navigation satellites commonly use repeat ground track orbits [1]. With the development of civilian satellites technology, constellation composed of a number of satellites plays an important role in remote sensing [2]. The Earth observation missions often require the constant solar illumination, the same ground resolution, and small repeat cycles, which often results in the design of Repeat Sun-Synchronous Orbit (RSSO) satellites as the most suitable one. This kind of satellites allows the observation of a given region of the Earth at the same local time after a time interval [3, 4]. The approach to design repeat ground track orbit for the Earth observations (EO) is quite mature [5, 6]. As well, the RSSO satellites are also used for Mars observations [7–10].

Repeat ground track (RGT) orbits allows a satellite to reobserve the same area after a repeat cycle. Some articles have shown the various uses of RGT orbits. Fu et al. [11] presented a strategy for design and maintenance of low RGT successive-coverage orbits and their analysis is based on the drift over the entire ground track. Li et al. [12] introduced a special repeat coverage orbit which is a special class of RGT orbit, such orbits can visit a target site at both the ascending and descending stages in one revisit cycle. Circi et al. [13] showed the concepts of sliding ground track pattern, which allows one RGT orbit to transfer to another RGT orbit using a low-Δv technique. This technology guarantees the fulfillment of several objectives in the course of the same mission. Recent studies have shown the possibility of using the Periodic Multi-Sun-Synchronous orbits (PMSSOs) for Earth and Mars observation; these orbits allow the observation of the same area under different solar illumination conditions and have a repetition period of the solar illumination conditions which is multiple of the repeat cycle [9, 10]. Wang et al. [14] divided the region by latitude stripes. The relationship between the cumulative coverage and the altitude can be quickly got, which is helpful for orbit designer to select optimal orbits for Earth observation.

Revisit time (RT) of a single satellite is the time elapsed between two successive observations of the same ground point on the surface of the Earth [15]. Different from the repeat cycle which is only relevant to the satellite orbits, the revisit time is relative to both of the orbit and the payload of satellite, such as tilt angle and swath width [16]. Most of the previous papers which aim to design orbits for remote sensing concentrate on the repeat cycle and near-repeat cycle [4, 16]. However, they have not considered the revisit time when designing satellites. In general, the orbit design should be treated as a multidisciplinary process, which needs to consider the satellite system such as payload properties. Saboori et al. [17] proposed a multiobjective optimization tool to design repeat sun-synchronous orbits for remote sensing satellites; they considered the revisit time as a function of the tilt angle and side-lap of the satellite. However, the calculation in their work does not consider the subcycles of the orbit. Pie and Schutz [18] introduced the subcycles of repeat ground track orbits and the charts of subcycles are used to decompose the repeat cycle into three main subcycles.

Nadoushan and Assadian [19] presented a novel technique to design RGT orbit with desired revisit time and optimal tilt angle; their calculation is based on the analyses of subcycles. However, their approach could be used only when the repeat cycle is prime relative to the revisit time. When the repeat cycle is not prime relative to the revisit time, the design approach could not be used. As a result, a lot of feasible orbits which meet the mission requirements are ignored. As a design tool, it is preferable to conduct an ergodic performance on the altitude.

This paper proposes a novel technique to compute the revisit time and minimum revisit time of remote sensing satellites. The relationship between the revisit time and the tilt angle of a satellite can be computed fast by this technique. Compared to the approach proposed by Nadoushan and Assadian [19], when the swath width, side-lap, the range of altitude, and desired revisit time are given, a lot of orbit solutions which meet the mission requirements will be obtained fast. It will be helpful for the orbit designer to select the best orbits in all solutions.

Section 2 illustrates the orbital relationships that have to be satisfied to obtain regular cycles of observation of the Earth with a uniform ground track pattern. And the subcycles of repeat ground track orbit are considered and developed using Bezout's lemma. In the third section, the procedure of the proposed technique is raised to calculate the RT of satellite. At last, the technique is used to compute and select the best orbits according to the mission requirements. Finally, some cases are investigated for evaluation of the technique.

2. Repeating Sun-Synchronous Orbits and Subcycles

2.1. Repeating Sun-Synchronous Orbits. The repeating orbits are also known as the repeat ground track orbits, which are defined as orbits with periodic repeating ground tracks. Their ground track will repeat after a whole number of revolutions R in D nodal days. These orbits have good appearances for the Earth's coverage, which is good for remote sensing. For optical observations, it is important to ensure that illumination conditions remain the same or vary as little as possible when observing the same ground area; this is known as sun-synchronous orbit. We consider an intersection of the equator and a satellite's descending (ascending) ground track. For a satellite, the interval between two successive equatorial crossings of the ground track on the equator is

$$\Delta\lambda = T_N \left(\omega_E - \dot{\Omega}\right), \tag{1}$$

where ω_E is the Earth's rotation rate with respect to the vernal equinox. $\dot{\omega}$ is the variation rates of argument of perigee and $\dot{M}$ is the variation rates of mean anomaly. T_N is the nodal period of the motion of the satellite, which is expressed as

$$T_N = \frac{2\pi}{\dot{M} + \dot{\omega}}. \tag{2}$$

The condition for repeating ground track orbits can be written as

$$R \cdot T_N \left(\omega_E - \dot{\Omega}\right) = R \cdot \Delta\lambda = D \cdot 2\pi \tag{3}$$

or

$$R \cdot T_N = D \cdot D_N, \tag{4}$$

where R and D are positive integers and they are prime to one another. D_N is nodal day; it is expressed as

$$D_N = \frac{2\pi}{\omega_E - \dot{\Omega}}. \tag{5}$$

If the orbit is sun-synchronous orbit as well, the nodal precession rate $\dot{\Omega}$ equals the rotational angular speed of the Earth ω_S. A nodal day of the repeating sun-synchronous orbit is a solar day which is equal to 86400 s. This is a useful relationship unique to RSSOs when evaluating how fast the ground track advances in longitude as a function of time [4].

In engineering practice, the repeating factor Q represents the number of orbits completed per day. Q determines the location and sequence of all ground traces, which is defined as

$$Q = \frac{R}{D} = I + \frac{K}{D}. \tag{6}$$

In (6), 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 $0 \le K < D$.

This paper only considers the descending node passes or ascending node passes. The terms related to this article are defined as follows.

Definition 1. Fundamental interval S_Q: S_Q is the interval on equator between two successive ground tracks. $S_Q = 2\pi/Q = \Delta\lambda$.

Definition 2. Minimum interval S_D: S_D is the minimum interval on equator between two ground tracks after a repeat cycle. $S_D = S_Q/D$.

Table 1 shows the parameters of some repeating sun-synchronous satellite orbits.

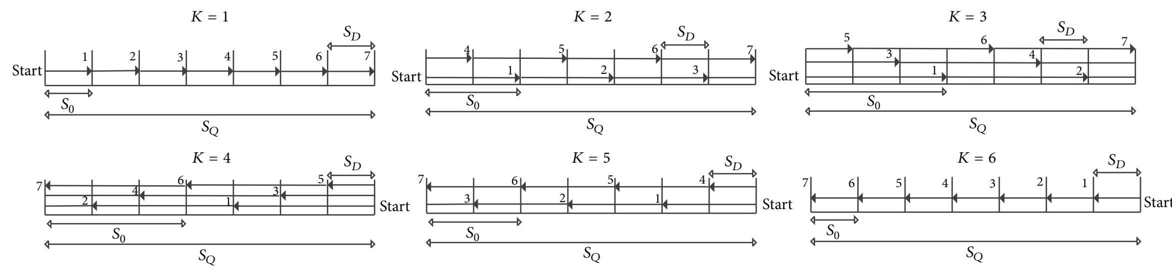

FIGURE 1: Ground track sequences for $D = 7$.

TABLE 1: Parameters of some repeating sun-synchronous orbits.

	a (km)	i (°)	I	K	D	S_Q (°)	S_Q (km)	S_D (°)	S_D (km)
A	605.512	97.81	14	6	7	24.23	2697.36	3.46	385.33
B	650.737	97.99	14	5	7	24.47	2723.54	3.50	389.08
C	696.701	98.18	14	4	7	24.71	2750.25	3.53	392.89
D	743.421	98.37	14	3	7	24.95	2777.48	3.56	396.78
E	790.919	98.57	14	2	7	25.20	2805.25	3.60	400.75
F	839.216	98.78	14	1	7	25.45	2833.59	3.64	404.80

Ground track analyses play an important role in designing the repeating sun-synchronous orbits. Every fundamental interval S_Q is divided into D minimum fundamental intervals by $(D - 1)$ time-successive ground tracks. The parameter K determines the way where these subdivisions are carried out. The minimum ground track distance S_0 on equator in consecutive nodal days can be expressed as follows:

$$S_0 = S_D \cdot K \quad \text{for } K < \frac{D}{2}, \tag{7a}$$

$$S_0 = S_D \cdot (K - D) \quad \text{for } K > \frac{D}{2}. \tag{7b}$$

Depending on the parameters K, the ground traces can be considered direct or skipping. If K is 1 or $D - 1$, then each successive trace falls next to the one which is before it. Take into account orbits named E, F in Table 1 as an example. The fundamental interval S_Q is divided into 5 equally spaced intervals. For the case of orbit F, the parameter K equals 1. The daily interval S_0 is equal to S_D and the ground tracks related to the successive nodal days are eastward shifted of S_D. For the case of orbit E, the parameter K is equal to 2. The daily interval $S_0 = 2S_D$ and the ground tracks related to the successive nodal days are eastward shifted of $2S_D$. Figure 1 shows the ground track sequences of the satellite when the parameter $D = 7$. In fact, if $S_0 > 0$, the progress of ground trace is eastward and if $S_0 < 0$, the progress is westward.

2.2. Subcycles in a Repeat Cycle. According to the paper [20, 21], a subcycle is an integer value of days after which the ground track of the satellite nearly repeats itself within a small offset. A subcycle of a satellite can be viewed as a near-repeat cycle which is equal to an integer number of nodal days.

From Figure 1, we can get a conclusion: for any repeat ground track orbits whose values of K and D are decided, there exists a time of interval d_1 nodal days after which the ground track of the satellite passes at a minimum interval S_D of the original node to the east. The ground track will pass at a minimum interval S_D of the original node to the west in $(D - d_1)$ days.

In Lim and Schutz's definition, there are no specifics given for the offset, other than being "small" [21]. The offset is always considered to be equal to a minimum interval S_D in some literatures [16, 18].

However, for different purpose, it may be required to obtain the subcycle of a RGT orbit with a specific offset. The analyses for subcycles have a significant role in designing RGT orbits; in this paper, the small offset is redefined and replaced by a multiple of minimum intervals S_D. For a specific value D, there exists a large range of different subcycle patterns due to the value K. The approach to calculate subcycles of a satellite is presented in the paper [18]. Basically, the definition of subcycles is based on *Bezout* lemma, which can be expressed as [22]

$$d \cdot K - m \cdot D = k, \tag{8}$$

where d, m, and $k \neq 0$ are integer numbers. An integer solution d exists if and only if the parameter k is a multiple of the great common divisor of K and D. Since the value K and value D are coprime to one another, so if k is an integer number, the *Bezout* lemma ensures the existence of the solution. In (8), a subcycle d_k is the number of days after which the ground track will repeat itself with an offset equal to $k \cdot S_D$. The subcycles can be, respectively, labeled $(d_k, k \cdot S_D)$. For example, the first subcycle d_1 is the number of days required for the ground track to pass an offset S_D of the original descending node. Since the offset can be east or west, so the first subcycle d_1 has two values $d_{1\min}$, $d_{1\max}$ and $d_{1\max} > d_{1\min}$. And two values are relative to each other by $d_{1\min} = D - d_{1\max}$.

Orbit data of HJ-1A is used in this section, HJ-1A is a Chinese satellite of satellite constellation which aims to the environment monitoring and forecasting, and the design goal is to cover the Earth within four days [6]. Choose the orbit of HJ-1A as an example of which the parameter $Q = 14 + 23/31$. In Table 2, we present the subcycles of HJ-1A when setting different values of k. As illustrated in Table 2, when the required offset is twice as long as S_D, the corresponding subcycles are 23 days or 8 days. The 23 days of subcycle is relative to east offset which is labeled $(23, 2S_D)$, while the 8

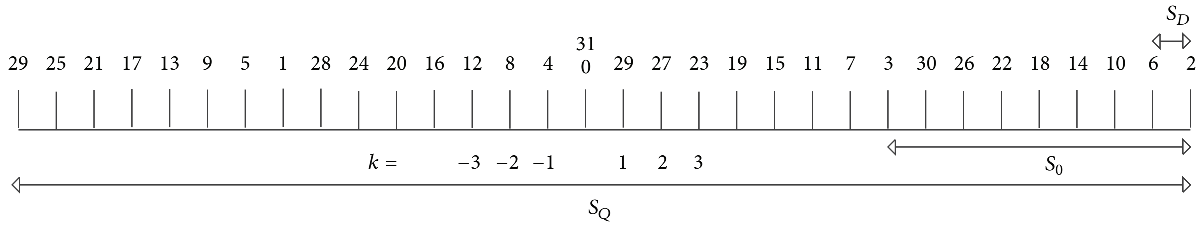

FIGURE 2: Ground track sequences when the parameter $Q = 14 + 23/31$ and subcycles corresponding to different offsets.

TABLE 2: Subcycles for a RGT orbit of which the parameter $Q = 14 + 23/31$.

K	D	k	Subcycles d (days)	Labeled
23	31	1	27	$(27, S_D)$
23	31	−1	4	$(4, -S_D)$
23	31	2	23	$(23, 2S_D)$
23	31	−2	8	$(8, -2S_D)$
23	31	3	19	$(19, 3S_D)$
23	31	−3	12	$(12, -3S_D)$

days is relative to a west offset which is labeled $(8, -2S_D)$. The temporal order of subsatellite trackes is illustrated in Figure 2.

3. Revisit Time and Optimization in the Satellite Design

In this section, the revisit time of a satellite is discussed. Revisit time (RT) of a single satellite is the time elapsed between two successive observations of the same ground point using off-nadir pointing of the payload or the attitude of the satellite [15]. The revisit time is relevant to both of the orbits and the payload of the satellite, such as tilt angle and swath width [16]. In practice, a satellite's optical instrument can view an area (using off-nadir observation) before and after the orbit passes over it. Off-nadir observation of a ground area is possible in two ways. The first one is the swath width of a sensor which is wide enough to cover the adjacent ground tracks, which is illustrated in Figure 3, where α is the half of field of view (FOV) angle. Another one is using the attitude maneuvers (tilt angles) $\pm\theta$ of the satellite with a small swath width, which is illustrated in Figure 4, and where θ is the tilt angle of the satellite. In either case, the satellite in adjacent orbits can observe the ground target, thus making the revisit time less than the repeat cycle.

3.1. Maximum Revisit Time. It should be noted that, in the case of a satellite with a swath width less than the minimum interval S_D and with no tilting capacity, the revisit time (or equivalently maximum revisit time) is equal to the repeat cycle. For these orbits, the revisit time of ground point at equator covered by the field of regard (FOR) of the satellite payload is equal to the repeat cycle. In addition, complete coverage at equator cannot be provided by the satellite and the revisit time is only related to the points which can be covered by the sensor. FOR is the area covered by a detector or sensor when pointing to all mechanically possible positions which is different from the FOV. The FOV is the area covered by the sensor or detector when pointing to one position [17].

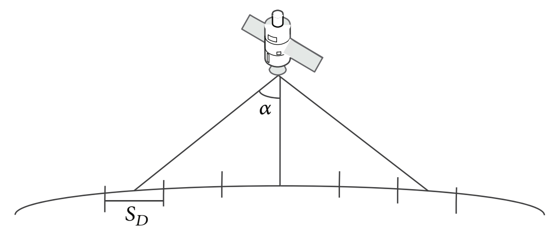

FIGURE 3: Observe the ground target by a sensor with a wide swath width.

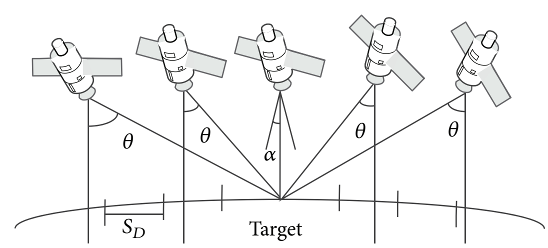

FIGURE 4: Observe the ground target from adjacent orbit using tilt capacity.

The maximum cone angle ϕ where the surface of the Earth can be observed by a satellite is calculated as follows [19]:

$$\phi = \sin^{-1} \frac{R_E}{R_E + a}, \tag{9}$$

where a is the altitude of orbit and R_E is the mean radius of the Earth.

3.2. Calculation of Revisit Time. The calculation of the revisit time is divided into two kinds of cases. The first case is where the sensor has a wide swath width with no tilting capacity; another case is that the sensor with tilting capacity has a small swath width. In either case, the maximum revisit time is smaller than the repeat cycle of the orbit. In both two cases, we can get the swath width ω corresponding to FOV, which can be calculated as follows [4]:

$$\omega = R \left\{ 2 \sin^{-1} \left(\frac{R + a}{R} \sin \frac{\text{FOV}}{2} - \text{FOV} \right) \right\}. \tag{10}$$

When calculating the swath width corresponding to the FOR, the FOV in (11) should be replaced by the FOR. In order

Table 3: Different revisit time of P6 satellite with different tilt capacity and side-lap.

n	Side-lap (%)	Tilt angle range (°)	S'	RT (days)	RT_{min} (days)
1	0	[7.98, 15.60)	{0, 5, 19}	14	5
2	0	[15.60, 22.60)	{0, 5, 10, 14, 19}	5	4
3	0	[22.60, 28.81)	{0, 5, 9, 10, 14, 15, 19}	5	1
4	0	[28.81, 34.20)	{0, 4, 5, 9, 10, 14, 15, 19, 20}	4	1
1	5	[8.39, 16.37)	{0, 5, 19}	14	5
2	5	[16.37, 23.63)	{0, 5, 10, 14, 19}	5	4
3	5	[23.63, 30.01)	{0, 5, 9, 10, 14, 15, 19}	5	1
4	5	[30.01, 35.48)	{0, 4, 5, 9, 10, 14, 15, 19, 20}	4	1

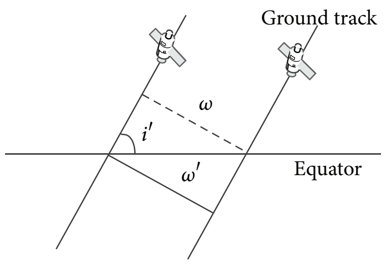

Figure 5: Apparent inclination i' and the swath on the equator ω'.

to get a more accurate result, the apparent inclination i' is introduced in this paper. Apparent inclination is the angle between the equator and the ground track of the satellite in Earth-centered Earth-Fixed Coordinate (ECEF) system. And for circular orbits, i' is defined as [22]

$$\tan i' = \frac{\sin i}{\cos i - 1/Q}. \tag{11}$$

In some cases, in order to get a better spatial resolution, a margin of safety must be taken into account. Assuming a 10% overlap is required, so the effective swath width ω of the satellite should be replaced by 0.9ω.

The swath of the satellite on the equator ω' is depicted in Figure 5 and it can be calculated as follows [22]:

$$\omega' = \frac{\omega}{\sin i'}. \tag{12}$$

In order to achieve a complete longitude coverage on the equator in a repeat cycle D, ω' must be greater than the minimum interval S_D. When the swath width of the satellite is wide enough to cover several minimum intervals, the half of number of minimum separations n which can be covered is calculated as follows:

$$n = \operatorname{int}\left(\frac{\omega'}{2 \cdot S_D}\right), \tag{13}$$

where function $\operatorname{int}(x)$ is to get the integer part of x. According to (13), the number of minimum separation intervals which can be covered by the satellite payload is obtained. In this case, the satellite can observe the ground target with an offset which is smaller than $n \cdot S_D$, thus making the satellite in adjacent tracks able to observe the ground target as well. The feasible number n of minimum intervals S_D which can be covered by the satellite forms a set R, and $R = \{-n, -n+1, \ldots, -1, 0, 1, \ldots, n-1, n\}$.

Choose an element k in the set R, and bring it into (8); then the subcycle d_k can be obtained. Through this step, a set of subcycles S corresponding to the set R can be derived as

$$S = \{d_{-n}, d_{-n+1}, \ldots, d_{-1}, d_0, d_1, \ldots, d_n\}. \tag{14}$$

Next, the set of subcycles S should be sorted from small to large; the sorted set is named as S'. Assume that $S' = \{d_0, d_1, d_2, \ldots, d_{2n-1}, d_{2n}\}$. The revisit time (equivalently maximum revisit time RT_{max}) and the minimum revisit time RT_{min} can be computed as

$$RT_{max} = \max\{d_{k+1} - d_k\}, \quad 0 \le k < 2n, \tag{15a}$$

$$RT_{min} = \min\{d_{k+1} - d_k\}, \quad 0 \le k < 2n. \tag{15b}$$

Choose the orbit of HJ-1A as an example of which $Q = 14 + 23/31$. The swath on the equator of the satellite is 6 times as long as minimum interval S_D and $n = 3$ according to (13). So the set $R = \{-3, -2, -1, 0, 1, 2, 3\}$. The set of corresponding subcycles $S = \{12, 8, 4, 0, 27, 23, 19\}$ which is depicted in Table 2. According to (15a) and (15b), the revisit time of HJ-1A is 7 nodal days and the minimum revisit time is 4 nodal days.

Actually, different revisit time corresponds to the different tilt capacity and side-lap; Table 3 shows the different revisit time of P6 satellite [19] with different tilt capacity and required side-lap.

There are some analyses for Table 3 as follows:

(1) The revisit time and minimum revisit time of a satellite vary with different tilt angle and required side-lap.

(2) In some cases, an increase of tilt angle could not result in reduction of the RT. For example, when required side-lap is 5% and the tilt angle ranges from 8.39° to 23.63°, the revisit time remains 5 days.

The procedure to calculate the revisit time of a satellite with specific parameters is shown in Figure 6.

3.3. *Design for Remote Sensing Satellites.*

Orbital parameters design is a very important task during the mission analysis and design phase of a satellite. For remote sensing satellites,

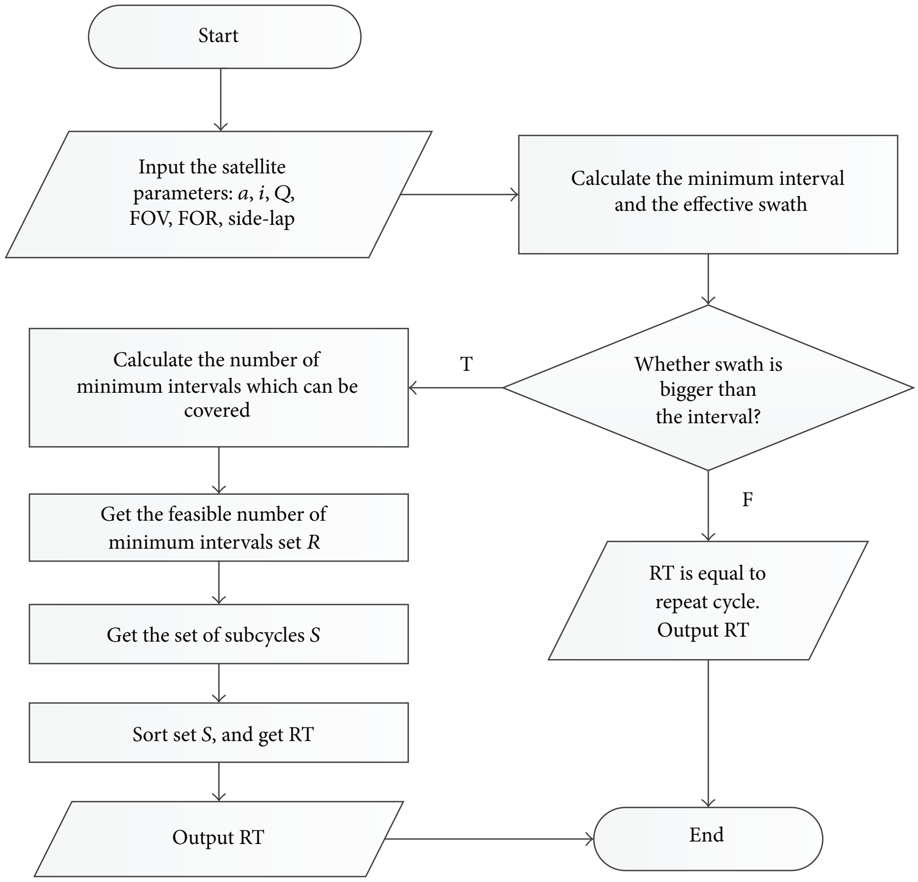

Figure 6: The procedure to compute the revisit time of a satellite.

the performance of a satellite can be represented in terms of resolution, revisit time, repeat cycle, tilt angle, and overlapping width [16]. Those characteristics should be taken into account in the orbit design of remote sensing satellites.

According to the approach shown in the last section, when the orbit and payload parameters are determined, the relationships between the tilt angle and the revisit time can be quickly obtained. This approach needs simple calculations and has high efficiency. In this section, the proposed approach is used to design and select the optimal orbits for remote sensing satellites.

When designing satellites for the Earth observation, the basic inputs are the orbital altitude range, the required side-lap, desired revisit time, and the maximum repeat cycle. The output of this approach is the minimum tilt angle in the premise of the desired revisit time and available side-lap constraint. This approach makes an ergodic search on the range of altitude and generates the orbital parameters which meet all of the operation constraints.

The calculation procedure of designing a satellite with required revisit time and optimal tilt angle are given as follows.

Step 1. Input the range of altitude, required side-lap, and desired revisit time $\mathrm{RT}_{\mathrm{des}}$.

Step 2. Input the maximum repeat cycle $D_{\max}$.

Step 3. Generate the set P composed of all the feasible orbits which is in the altitude range (the approach can be seen in [3]).

Step 4. Calculate the repeating factor Q and inclination i of each orbit. Since the orbit is sun-synchronous, so the inclination of orbit is determined. In this type of orbits, Q is only a function of the orbital altitude (the approach can be seen in [4]).

Step 5. Generate the maximum cone angle ϕ corresponding to each orbital altitude using (9).

Step 6. Choose an orbit of which the revisit time and tilt angle are not calculated in the solution set P.

Step 7. Search all the tilt angles which are smaller than maximum cone angle ϕ, and get the corresponding revisit rime (RT).

Step 8. If the RT is equal to $\mathrm{RT}_{\mathrm{des}}$, then record minimum tilt angle and the orbit in the set P'.

Step 9. Turn to Step 6 when an orbit of which the revisit time is not computed in the set P exists.

Step 10. Output all the orbits in the solution set P'.

Step 11. Compare the solutions and choose the optimal orbits in set P'.

Table 4: The orbital parameters and mission characteristics of two satellites.

Parameters	HJ-1A	P6 satellite
Orbit	Repeating Sun-synchronous	Repeating Sun-synchronous
Altitude (km)	649.093	816.964
Inclination (°)	97.9486	98.6799
Repeat cycle	457 orbits within 31 days	341 orbits within 24 days
Q value	14 + 23/31	14 + 5/24
Swath (km)	720	141
Tilting capacity (°)	0	26

Table 5: The revisit time of two satellites.

Parameters	HJ-1A	P6 satellite
S_D (km)	87.6915	117.522
Apparent inclination i' (°)	101.756	102.654
Effective swath on the equator ω' (km)	735.426	830.166
n	4	3
Feasible offset multiple R	$\{-4,-3,-2,-1,0,1,2,3,4\}$	$\{-3,-2,-1,0,1,2,3\}$
Set of subcycles S	$\{16,12,8,4,0,27,23,19,15\}$	$\{9,14,19,0,5,10,15\}$
Sorted set of subcycles S'	$\{0,4,8,12,15,16,19,23\}$	$\{0,5,9,10,14,15,19\}$
RT (days)	4	5
$\mathrm{RT}_{\min}$ (days)	1	1

4. Case Studies

4.1. Calculation of Revisit Time. The proposed technique is applied to compute the revisit time of some remote sensing satellites. HJ-1A [2] and P6 satellite [19] are chosen to verify the method. The orbital parameters and mission characteristics are presented in Table 4.

It could be found that the former satellite has a wide swath width while the latter satellite has a tilting capacity with a narrow swath. Utilizing the proposed technique, the revisit time of two satellites are calculated and presented in Table 5.

From Table 5, the maximum time gap between two successive observations of the HJ-1A satellite is 5 days. Actually, the revisit time of the HJ-1A is designed as 4 days [2], which can be seen in Table 4. At the same time, from Table 5, the revisit time of the P6 satellite is 5 days, which equals the values given in Table 4. These two cases demonstrate the accuracy of the proposed technique.

4.2. Optimization Design for Remote Sensing Satellites. In this section, some optimizations will be implemented on the P6 satellite. Since the altitude of the P6 satellite is 816.964 km, so we search all the feasible orbits in the altitude range from 810 km to 820 km. In Step 1, the swath width of satellite is 141 km, the required side-lap is set to 0%, and the required revisit time is equal to 5 nodal days. Table 6 illustrates the number of the orbits in set P and P' with different maximum repeat cycle $D_{\max}$.

In Step 2, the maximum repeat cycle is set to 100 days. Compute all the orbits in set P and all the orbit solutions which meet the mission requirements will be obtained. Figure 7 illustrates the feasible orbit solutions within $\mathrm{RT}_{\mathrm{des}} = 5$ when $D_{\max} = 100$; Figure 8 illustrates the feasible orbit solutions within $\mathrm{RT}_{\mathrm{des}} = 5$ when $D_{\max} = 200$.

Table 6: The number of the orbits in sets P and P' with different $D_{\max}$.

$D_{\max}$ (days)	Number of the orbits In the set P	Number of the orbits In the set P'
20	4	2
40	16	14
60	34	32
80	58	56
100	88	86
200	356	354

Table 7: Parameters and characteristics of some orbit solutions within $\mathrm{RT}_{\mathrm{des}} = 5$.

Solution parameters	Sol.1	P6 satellite	Sol.2
Altitude (km)	814.967	816.96	813.917
Inclination (°)	98.6716	98.6799	98.6671
Q value	14 + 3/14	14 + 5/24	14 + 5/23
Revisit time (days)	5	5	5
Minimum tilt angle (°)	13.5074	15.604	16.2889

In Figures 7 and 8, some orbit solutions termed, respectively, as Sol.1, Sol.2 in all feasible orbit solutions are shown in Table 7.

The most remarkable solutions are Sol.1, Sol.2, and the case of P6 satellite. Of course, Sol.1 could be the best choice since its tilt angle is the smallest among three solutions.

Figures 9 and 10 illustrate all the orbits which can meet the conditions where revisit time is 4 days in the altitude range of 810 km–820 km.

Table 8: Parameters and characteristics of some orbit solutions within $RT_{des} = 4$.

Solution parameters	Sol.3	Sol.4	Sol.5	P6 satellite
Altitude (km)	812.285	810.579	814.967	816.96
Inclination (°)	98.6602	98.653	98.6716	98.6799
Q value	14 + 2/9	14 + 5/22	14 + 3/14	14 + 5/24
Revisit time (days)	4	4	4	4
Minimum tilt angle (°)	20.4385	24.5137	25.4045	28.81

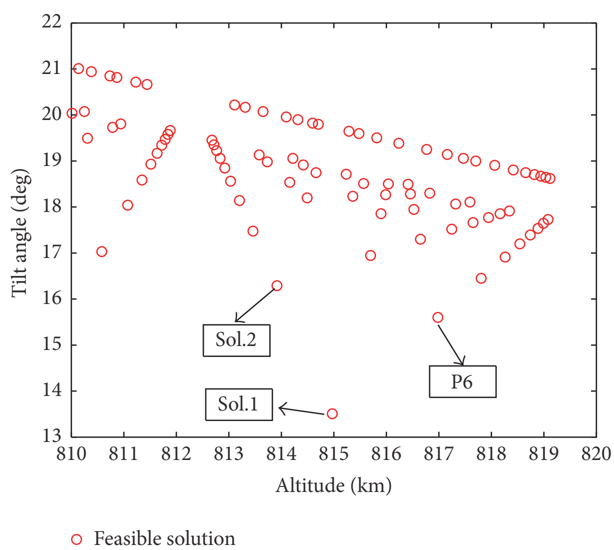

Figure 7: Feasible orbit solutions within $RT_{des} = 5$ when repeat cycle $D_{max} = 100$.

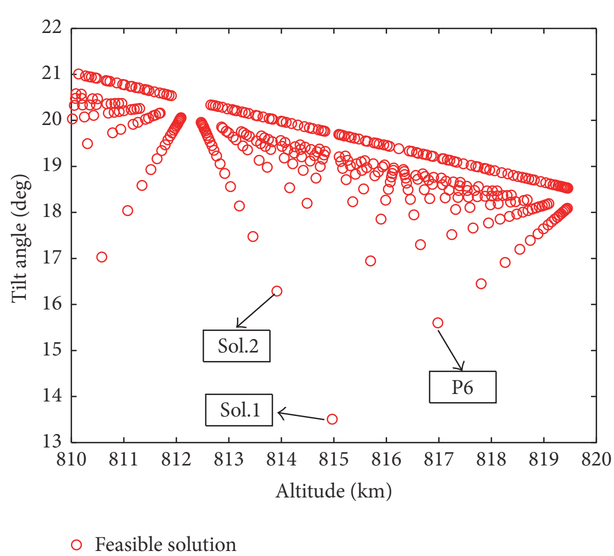

Figure 8: Feasible orbit solutions within $RT_{des} = 5$ when repeat cycle $D_{max} = 200$.

In Figures 7 and 8, some orbit solutions termed, respectively, as Sol.3, Sol.4, and Sol.5 in all feasible orbit solutions are shown in Table 8.

The most remarkable solutions are Sol.3, Sol.4, and Sol.5 and the case of p6 satellite. Of course, Sol.3 could be the best choice since its tilt angle is the smallest among three solutions.

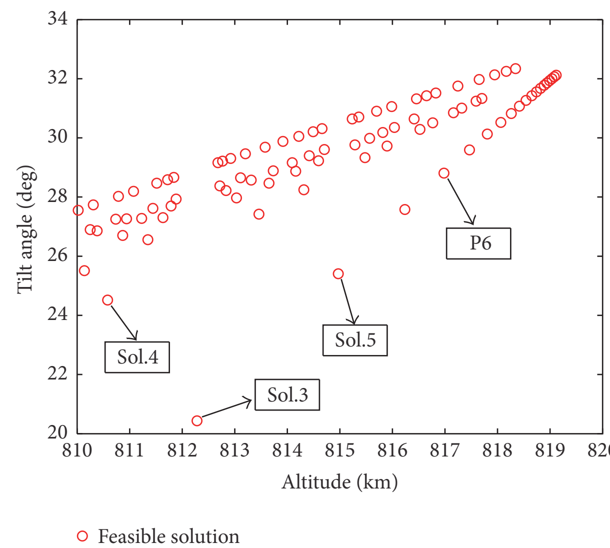

Figure 9: Feasible orbit solutions within $RT_{des} = 4$ when repeat cycle $D_{max} = 100$.

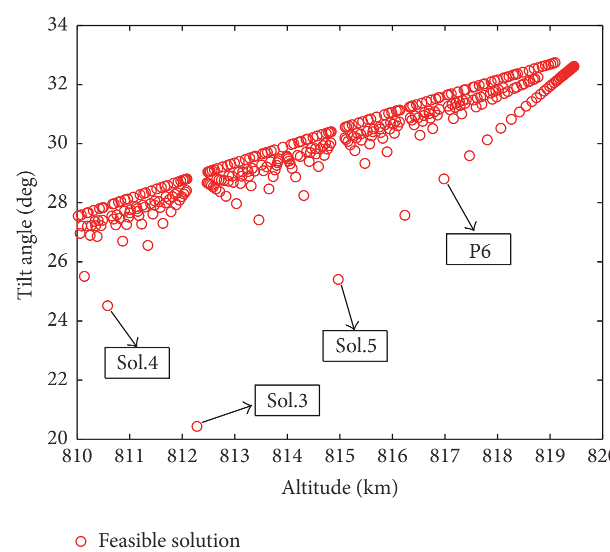

Figure 10: Feasible orbit solutions within $RT_{des} = 4$ when repeat cycle $D_{max} = 200$.

Comparing the feasible orbit solutions in Figures 7 and 10, there are some analyses as follows:

(1) With the increase of maximum repeat cycle, the number of feasible orbit solutions will increase as well. At the same time, the best orbit of which the desired revisit time is 5 days is not the same as the best orbit of which the desired revisit time is 4 days.

(2) Sol.3, Sol.4, and Sol.5 have different repeat cycles and ground tracks, but all of them can observe the same ground target within 4 days. According to the paper [13], when the orbital altitude is approximately the same, one orbit can transfer to another orbit using a low Δv technique. This technology guarantees the fulfillment of several objectives in the course of the same mission, which is useful for different task.

5. Conclusion

A novel technique which takes into account the orbits and the payload is proposed to calculate the revisit time of a remote sensing satellite. The technique is discussed using the Bezout equation and takes the gravitational second zonal harmonic into consideration. The relationships between altitude and minimum tilt angle can be quickly obtained when the revisit time is determined. So, the proposed technique can make an ergodic search on the altitude and a lot of orbit solutions which meet the mission requirements will be got fast as well. Therefore, the approach can be used in the optimization design for remote sensing satellites. It will be helpful for orbit designer to calculate and select the best orbits in all solutions.

Competing Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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