The Global Coverage of a Remote-sensing Satellite in a Sun-synchronous Orbit*

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The global coverage of a Sun-synchronous orbit is investigated in this paper to provide reasonable references for the orbit design of remote-sensing satellites. Firstly, the connection between revisiting and repeat ground-tracking is bridged applying the concept of $Q$ value. Starting from the $Q$-value-determined base interval, a mathematical expression is derived for the accessing sequence of the nodes. Then, the coverage percentage is acquired by mixing the accessing sequence and coverage area, which depends on the orbital altitude and observation angle. Finally, the coverage of a satellite in a Sun-synchronous orbit is illustrated from three aspects: time-varying coverage percentage, minimal coverage time and minimal coverage area, which depends on the orbital altitude and observation angle. Validation of the existing satellites’ parameters shows that the method proposed in this paper is simple but effective, and these coverage analyses will contribute to shortening the time to design an optimal Sun-synchronous orbit for remote-sensing satellites.

Key Words: Global Coverage Properties, Remote-sensing Satellite, Sun-synchronous Orbit, Accessing Sequence, Coverage Percentage

1. Introduction

There has been great progress made in Earth observation satellites, such as remote-sensing satellites, in recent years. The observation resolution has achieved one meter, and even the sub-meter level. Thus, Earth observation possesses important applications in military, civilian and other fields. As the optical payloads carried by remote-sensing satellites (e.g., on-board charge-coupled device (CCD) cameras) require comparatively stable sunshine conditions, a Sun-synchronous orbit (SSO) is widely adopted for remote-sensing satellites. Global coverage is an important parameter for Earth observation satellites. Many researchers have done a lot of work on SSOs and related coverage property. Casey and Way1 proposed the concept of “$Q$ value” and studied the accessing sequence of a repeat-groundtrack (RGT) orbit during one repeat cycle applying the $Q$ value. In order to guarantee efficient coverage, Aoripmai and Palmer2 proposed an orbit control strategy for Earth observation satellites based on a set of orbital elements, which are called “epicycle elements.” Similarly, Fu et al.3 presented a strategy for the design and maintenance of a low-Earth RGT successive-coverage orbit, which contributes to completing global coverage. However, it will cost a great deal to apply this type of orbit control. Recently, Xu and Huang4 presented a semi-analytic methodology to design a specified revisiting orbit that implements global coverage of the Earth; however, they did not investigate the coverage properties of a SSO. From the viewpoint of constellation design and repeating orbit theory, the orbit adopted by the HJ-1A/1B mission5 possesses global coverage ability. However, this method did not reveal the general rule of the coverage property for a SSO. Actually, little research has been done about the systematic relationship be-

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Nomenclature

\[ P_{EO} : \] nodal day  
\[ P_{nod} : \] nodal period of orbit  
\[ D : \] repeat cycle of RGT orbit  
\[ N : \] satellite’s revolution times during one repeat cycle  
\[ v : \] integer after $Q$ value is rounded down  
\[ d : \] numerator of $Q$ value  
\[ \delta_c : \] grid interval  
\[ \delta_b : \] base interval  
\[ R_e : \] radius of Earth  
\[ \omega_E : \] angular velocity of Earth’s rotation  
\[ W_{GT} : \] secular rate of RAAN  
\[ f : \] fractional part of $Q$ value  
\[ k : \] denotes some integer  
\[ i : \] denotes some integer  
\[ Y : \] ordinal position of node at $k$th day  
\[ y : \] position of node at $k$th day  
\[ W : \] satellite’s coverage area  
\[ h : \] orbital altitude  
\[ a : \] field of view for satellite-borne camera  
\[ \beta : \] max roll off-nadir angle  
\[ \gamma : \] observation angle  
\[ w : \] ratio between $W$ and $\delta_b$  
\[ x : \] fractional position of node at $k$th day  
\[ x_1 : \] left boundary of coverage area  
\[ x_2 : \] right boundary of coverage area  
\[ C_k : \] coverage percentage within $k$ days  
\[ \Delta C_k : \] increment of coverage percentage at $k$th day

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between the coverage percentage and other factors for a SSO. In this paper, we address the coverage property of a SSO. Firstly, the accessing sequence of a SSO is presented through analyzing RGT orbit characteristics. Secondly, considering the cameras carried by satellites, we present an effective method that is used to yield the coverage percentage within specific days. Furthermore, the existing satellites’ parameters validate that the method is powerful enough to provide a fast design for global coverage with a given observation angle. There are two principal contributions: 1) a global distribution of orbit altitude \( h \) and observation angle \( \gamma \), and the coverage time related to every pair of \((h, \gamma)\); and 2) considering the influence of transfer errors on the coverage, both orbit control thresholds and attitude control thresholds are provided.

### 2. The Concept of \( Q \) Value

The ground track will be repeated if the satellite revolves around the Earth integer times during integer nodal days. Thus, the constraint of the RGT orbit can be expressed as:\(^1\)

\[
DP_{EO} = NP_{nod}
\]  
\( (1) \)

where \( P_{EO} \) is the nodal day and \( P_{nod} \) is the nodal period of the orbit. \( D \) and \( N \) are co-prime integers; \( D \) is the number of nodal days in one repeat cycle of the RGT orbit and \( N \) is the number of satellite’s revolutions during one repeat cycle. Generally, the ratio between \( N \) and \( D \) is defined as the \( Q \) value of the orbit. This value can parameterize the accessing and coverage properties of the orbit.

Specifically, the nodal day will be equal to the solar day for the SSO, namely \( P_{EO} = 86400 \) s. Thus, the \( Q \) value of the SSO can be defined as:

\[
Q = \frac{N}{D} = \frac{86400}{P_{nod}}
\]  
\( (2) \)

The \( Q \) value represents the number of satellite revolutions during one solar day, and it can be transformed as the following expression in order to facilitate exploring the orbital properties:

\[
Q = v + \frac{d}{D}
\]  
\( (3) \)

where \( v \) is the integer after the \( Q \) value is rounded down and \( d = N - vD \).

### 3. Accessing and Coverage of Orbits

The \( Q \) value determines the position of ground tracking and the accessing sequence of orbit in one repeat cycle. As for single-pass imaging coverage satellites, it’s hardest for them to achieve global coverage at the equator, which is the longest circle around the Earth. This section investigates the relationship between \( Q \) value and accessing sequence and the orbit’s coverage properties. Firstly, we give the accessing sequence of a RGT orbit during one base interval at the equator, which will be used to derive the accessing sequence of the SSO in this interval. Secondly, combining the accessing sequence and coverage area of the satellite, this section also gives the method that can be utilized to obtain the coverage percentage.

#### 3.1 Accessing orbit properties

According to Section 2, the RGT orbit will complete \( N \) revolutions around the Earth during \( D \) days. Thus, \( N \) ascending nodes are employed to divide the Earth’s equator into \( N \) equal parts (the same treatment can be applied to descending nodes as well). The distance between two adjacent nodes is defined as the grid interval \( \delta_y \) at the equator, which denotes the distance between two successive nodes in time.

\[
\delta_y = \frac{2\pi R_e}{N}
\]  
\( (4) \)

where \( R_e \) is the radius of the Earth. Additionally, the satellite revolves around the Earth \( Q \) times during one day, and the distance between two successive accessing nodes is called “the base interval at the equator,” which denotes the distance between two successive nodes in time.

\[
\delta_y = \frac{R_e(\omega_E - W_\Omega)}{Q} = R_e(\omega_E - W_\Omega)P_{nod}
\]  
\( (5) \)

where \( \omega_E \) is the angular velocity of the Earth’s rotation and \( W_\Omega \) is the secular rate of RAAN. The quantity of \( P_{EO} = 2\pi/(\omega_E - W_\Omega) \) is applied in Eq. (5).

The \( N \) nodes at the equator can be used to parameterize the accessing conditions during one repeat cycle, which is \( DP_{EO} \). However, it may cause significant inconvenience when the repeat cycle time is relatively longer. Considering the properties of a RGT orbit, the nodes in the base interval, rather than all of the nodes, can be utilized to reflect the accessing property of the orbit. Utilizing Eq. (5), the relationship between the grid interval and base interval can be derived as \( \delta_y = D\delta_y \). It is indicated that one base interval can be divided into \( D \) grid intervals. In the traditional design methodology, the accessing sequence is confirmed from the schedule of node-to-node enumeration.\(^4\) It is still labor-consuming when \( D \) is large, so it is necessary to derive a mathematical expression to determine the accessing sequence automatically.

Take the base interval next to the starting point as an example. The nodes at the equator are numbered as shown in Fig. 1, where the numbers outside of the arc (from \( N \) to \( N - D \)) are adjacent node ordinals, while the corresponding inner ones (from 0 to \( D \)) are used in this paper. Then, \( Y_{k} / y_{k} \) is the position of the node at the \( k \)th day.

It can be concluded that the ordinal position of node \( y \) at...
the $k$th day satisfies the following equation:
\[ y_k = \text{mod}(kd, D) \quad 0 < k < D \]  
\[ \text{Eq. (6)} \]
where “mod” is the function that is used to take the remainder of two integers. From Fig. 1, the counterpart of $y_k$, $Y_k$, is obtained as
\[ Y_k = N - \text{mod}(kd, D) \]  
\[ \text{Eq. (7)} \]
We use a mathematical induction technique to show that Eq. (7) is equivalent to the $k$th day accessing node in this interval. Clearly, on the first day when $k = 1$, the position of the accessing node in this interval is $vD$. It can then be written as $Y_1 = N - d = N - \text{mod}(d, D)$.

Suppose that the position of the $(k-1)$th day is
\[ Y_{k-1} = N - \text{mod}((k-1)d, D) \]  
\[ \text{Eq. (8)} \]
Then, after $v$ times passes in one day, the position at the $k$th day is
\[
\begin{align*}
Y_k &= Y_{k-1} - d + D & \text{if } \text{mod}((k-1)d, D) > D/2 \\
Y_k &= Y_{k-1} - d & \text{if } \text{mod}((k-1)d, D) < D/2
\end{align*}
\]
\[ \text{Eq. (9)} \]
Rewrite Eq. (8) as $Y_{k-1} = N - ((k-1)d - iD)$, where $(k-1)d = iD + \text{mod}(d, D)$. By substituting this into Eq. (9), Eq. (7) and Eq. (6) are satisfied.

It can be seen from Eq. (6) that the numerator $d$ plays an important role in the accessing sequence during one repeat cycle. The sketch map of accessing sequence of the RGT orbit with the value of $y$ in Eq. (6) is shown in Fig. 2.

Two major conclusions can be acquired as follows.

1) If $d = 1$ or $d = D - 1$, ground tracking will move eastward or westward one grid interval based on ground tracking the previous day. This type of orbit achieves continuous coverage day by day. However, it is difficult for this orbit to revisit some specific area within a short time.

2) If $d \neq 1$ and $d \neq D - 1$, ground tracking will move several intervals based on the ground track of the previous day. This kind of orbit can satisfy the demands of a fast revisit.

Based on the accessing sequence of a RGT orbit during one repeat cycle, we investigate the accessing properties of a SSO. The base interval of a SSO, one repeat cycle, we investigate the accessing properties of

\[ f = Q - \lfloor Q \rfloor \]  
\[ \text{Eq. (10)} \]
where $\lfloor Q \rfloor$ is the function that rounds down the fraction. Notice that $f = d/D$. For this SSO, the position of the node at the $k$th day is $x_k = y_k/d$, which then satisfies the following equation:
\[ x_k = kf - \lfloor kf \rfloor \]  
\[ \text{Eq. (11)} \]
Similarly, the accessing sequence of the SSO is shown in Fig. 3.

The fractional-form expression of the accessing sequence obtained makes it possible to automate the coverage computation by a script. It can be considered as one of the contributions achieved in this paper.

3.2. Orbit coverage properties

The satellite’s coverage area $W$ is subject to the orbital altitude $h$, camera field of view (FOV) $\alpha$ and the maximum roll off-nadir angle of the satellite $\beta$. Quantitatively, the coverage area of an Earth observation satellite at the equator is shown in Fig. 4. Therefore, the coverage area can be obtained utilizing the following equation\(^{4}\):

\[ W = 2R_e \left[ \arcsin \left( \frac{h + R_e \sin \gamma}{R_e} \right) - \gamma \right] \]  
\[ \text{Eq. (12)} \]
where $\gamma$ is defined as the observation angle that is equal to $\beta + 0.5\alpha$.

In order to facilitate analyzing the coverage properties of the satellite, the ratio between the coverage area $W$ and base interval $\delta_h$ is defined as the relative coverage area $w$, which is calculated utilizing the following equation:
\[ w = \frac{W}{\delta_h} \]  
\[ \text{Eq. (13)} \]
From the previous sections, it is indicated that the equator of the Earth is covered with $Q$ base intervals. Furthermore, a satellite’s accessing and coverage properties are consistent in every base interval. Thus, one base interval can be chosen to present the coverage properties of the satellite. If the satellite can cover the entire area of the base interval within a certain duration, it will realize global coverage at the same time.

Combining the accessing sequence in the base interval and relative coverage area, we present a method that is used to
calculate the coverage percentage during given a time interval. Firstly, the coverage percentage in the first day is calculated as shown in Fig. 5.

In Fig. 5, \( x_{11} \) and \( x_{21} \) are the boundaries of the coverage area at the first day. Obviously, \( x_{21} - x_{11} = \omega \), and the coverage percentage at the first day \( C_1 \) is equal to \( \omega \). Later, the coverage percentage within \( k \) days \( C_k \) can be calculated by adding the increment of coverage percentage at the \( k \)th day (denoted as \( \Delta C_k \)) to \( C_{k-1} \). In other words, \( C_k = C_{k-1} + \Delta C_k \). The sketch map for both separated and overlapped regions caused by the nodes of two days is shown in Fig. 6.

As shown in Fig. 6(a), if there is no overlap between \( C_k \) and \( C_{k-1} \), \( \Delta C_k = \omega \). Otherwise, \( \Delta C_k = x_{1,k} - x_{1,k-1} = x_{2,k} - x_{2,k-1} \), which is indicated in Fig. 6(b). The existence of an overlapped area depends on the altitude of the orbit chosen and observation angle of the satellite.

So far, this paper has presented the method used to calculate coverage percentage within certain days. It mixes the fractional-form accessing sequence into coverage percentage accumulation and the calculation is conducted on a computer. Additionally, this method will be utilized to investigate the global coverage properties of SSO.

4. Property Analysis of Global Coverage

Based on the accessing sequence and coverage percentage determination method in Section 3, the property analysis of global coverage for the SSO is addressed in this section, including time-varying coverage percentage and the minimal coverage time required by global coverage that contributes to designing proper orbit under corresponding mission requirements and the minimal observation angle needed for global coverage.

4.1. Time-varying analysis of coverage percentage

The coverage percentage of a satellite within certain working days is subject to the orbital altitude and observation angle. Numerical simulation is carried out to investigate the relationship between coverage percentage and the three variables. The following outlines the procedure. First, the range of altitude [550, 900 km], observation angle [10°, 50°] and duration [2, 9 d] are input. Then, for each altitude and observation angle, the nodal period \( P_{nod} \) is determined by mean rate of mean argument of mean latitude,1) passes per day \( Q \) utilizing Eq. (2), and area ratio \( \omega \) utilizing Eq. (13). At the \( k \)th day, the accessing sequence \( x_k \) is determined utilizing Eq. (11), and with it, the increment of coverage percentage \( \Delta C_k \) utilizing the method demonstrated in Fig. 6. Finally, going through the range of altitude, observation angle and integrating the range of working days, the temporal coverage percentage is obtained, as shown in Fig. 7.

Figure 7 gives the changing trends of coverage percentage. The following conclusions can be obtained: 1) Larger observation angle and longer working days can increase the coverage percentage. 2) The coverage percentage shows a near-symmetrical distribution along the orbital altitude. That’s more, the orbits with altitudes of 560 km and 888 km are considered to be the approximate boundaries, and the 725 km orbit is the near-symmetrical axis. The boundary altitudes of 560 km and 888 km correspond to the \( Q \) values of 15 and 14, respectively. The integral \( Q \) values imply that the ground track of the satellite will repeat in just one day. Therefore, the gap between sub-satellite points will re-
main indefinitely and global coverage will never be reached, even when the observation angle or working days are increased. Similarly, the altitude of 725 km leads to the $Q$ value of 14.5, which infers a two-day repeat cycle and bad performance in coverage percentage. The remaining $Q$ value in the interval [14, 15] displays a larger denominator and complementary numerator, which means longer repeat cycle (or better performance in coverage percentage shown later in Fig. 9) and similar performance. Therefore, the valleys in coverage percentage result in the boundaries and near-symmetrical axis.

The practical significance of Fig. 7 is to provide a reasonable orbital altitude range for a satellite with a specific observation angle and number of working days. For example, if one mission requires a satellite with a 35° observation angle to complete global coverage within three days, the reasonable altitude range can be determined utilizing the following two steps: 1) Accumulate the coverage percentage within three days by employing the procedure proposed in this subsection. 2) Choose the reasonable altitude where the coverage percentage is equal to 1.0. As shown in Fig. 8, the reasonable altitude ranges for the example are chosen as [660, 680 km] and [760, 790 km]. These altitude ranges can be regarded as the initial values for orbit optimization. Moreover, according to the relationship between the coverage percentage and orbital altitude in Fig. 8, it can also provide orbit control thresholds for orbit altitude and attitude control thresholds to increase observation angle as well, which can be regarded as one of the innovations introduced in this paper.

### 4.2. Minimal coverage time analysis

From the engineering aspect, usually a remote-sensing satellite must accomplish global coverage within a certain number of working days (i.e., coverage percentage = 1.0). By accumulating the coverage percentage on the ergodic altitudes and observation angles until approaching 1.0, the relationship between the days required for global coverage and orbital altitude $h$, and the observation angle $\gamma$, are presented in this section and shown in Fig. 9. For a better understanding and illustration, if the number of days required to obtain global coverage is longer than 10 days, the color does not darken. As seen in Fig. 9, it is indicated that the number of days required for global coverage depends closely on the orbital altitude and observation angle. Hence, the selection of orbital altitude can be determined applying the days required for global coverage and a certain observation angle. Table 1 lists the parameters of several existing remote-sensing satellites, which are denoted by the corresponding white spots in Fig. 9 as well.

The consistency of satellite data and the plot in Fig. 9 validate the method for determining coverage percentage proposed in this paper. The conclusions can be obtained through analyzing corresponding data, listed as follows.

1) When the altitude is lower than 550 km (denoted as Region I in Fig. 9), if the practical mission requires the satellite to complete global coverage within four days, the observation angle of the satellite must be greater than 40°. However, a larger roll off-nadir angle makes this difficult from the engineering aspect. Therefore, for this region it is suitable to design an orbit with a coverage time more than five days (e.g., ZY-3 mission). The candidate orbit in this region will possess the merit of higher image quality than other regions. Additionally, a multi-satellite constellation can cover the shortage of large coverage time by a single satellite. Therefore, a multi-satellite constellation with a small observation angle can choose the orbital altitude in this region.

2) When the orbital altitude is higher than 550 km but lower than 725 km (denoted as Region II in Fig. 9), global

| Orbital altitude (km) | Field of view (°) | Roll off-nadir angle (°) | Observation angle (°) | Coverage time (d) |
|-----------------------|------------------|--------------------------|----------------------|------------------|
| SJ-9A                 | 645              | 2.66                     | 35                   | 36.33            | 4                |
| ZY-1(02)C             | 778              | 4                        | 32                   | 34               | 3                |
| ZY-3                  | 505              | 5.64                     | 32                   | 34.82            | 5                |
| GF-1                  | 644              | 6.2                      | 35                   | 38.1             | 4                |
| CBERS-1               | 778              | —                        | —                    | 32               | 3                |
| ERS-1                 | 780              | —                        | —                    | 36               | 3                |
| GEOEYE                | 684              | —                        | —                    | 37               | 3                |
| ALOS                  | 691              | —                        | —                    | 44               | 2                |

Fig. 8. Coverage percentage within three days.

Fig. 9. Days required for global coverage.

Table 1. Remote-sensing satellites and corresponding parameters.
coverage can be achieved in four days in a majority of scenarios. Tiny deviations in orbital altitude and observation angle will not bring about a significant effect on the coverage percentage. Proper orbital altitude can make the satellite achieve global coverage within four days (e.g., SJ-9A\(^7\) and GF-1\(^8\) missions). Even when the deviation of orbital altitude is relatively large, the satellite still realizes global coverage within five to six days. Furthermore, if the satellite possesses better a observation angle, (e.g., ALOS mission\(^9\)), or its orbital altitude is relatively high in the region (e.g., GEOEYE satellite\(^10\)), global coverage can be achieved within three days. It should be noted that the orbit of ALOS is also a Sun-synchronous, sub-recurrent orbit with an orbit altitude of 691.65 km and repeat cycle of 46 days.

3) When the orbital altitude is higher than 725 km but lower than 900 km (denoted as Region III in Fig. 9), the 4-day global-coverage altitudes further release the restrictions on observation angle, and global coverage can even be achieved in three days. For example, the ZY-1(02)(C)\(^11\) CBERS-1/2\(^12\) and ERS-1\(^13\) satellites can achieve global coverage within three days using an observation angle of no more than 44°. In this region, global coverage can be mostly achieved in three or four days, which is less sensitive to change in orbital altitude and observation angle.

4) In summary, for a satellite with a small observation angle and low CCD pixel size in the satellite-borne camera, Region I can provide the reference to design the orbit, and it is better to adopt a multi-satellite constellation pattern. For a satellite with a small observation angle but considerable CCD pixel size, the orbit in Region III can enable the satellite to achieve global coverage in a short time period. And the 4-day global-coverage altitudes in Region II can satisfy most common remote-sensing satellite mission requirements.

5) The distribution graph in Fig. 9 also shows the satellite capacity curve for orbit design, which is similar to the payload capacity of rockets shown in a rocket user’s manual.\(^14,15\)

6) In previous designs of existing remote-sensing satellites, a series of Sun-synchronous, sub-recurrent orbits were designed to satisfy specific coverage requirements. From Fig. 9, it can be seen that these Sun-synchronous, sub-recurrent orbits are only part of revisiting orbits. There still exist many other revisiting orbits that are non-recurrent orbits.

4.3. Minimal observation angle analysis

The observation angle of a satellite plays a significant role in shortening the revisiting time of some hotspot area with the help of a specific orbital altitude. Therefore, it is important to analyze the minimal observation angle required for global coverage. In this section, the camera’s FOV is defined as 0°, thus the observation angle is equal to the roll off-nadir angle. Initiated at 10° and gradually increased to make the coverage percentage reaching 1, minimal roll off-nadir angle is found at a given coverage time and orbital altitude; namely, the \(Q\) value. Reviewing ergodic performance of the coverage time and orbital altitude, Fig. 10 indicates the relationship between the \(Q\) value and minimal observation angle required to achieve global coverage within a specific number of days.

The conclusions are backed by the information presented in Fig. 10 and listed as follows. 1) In a certain range of \(Q\) values, the increments of coverage time can effectively decrease the minimum required observation angle. 2) There exist minimums for the observation angle required to achieve global coverage within the same number of days (e.g., \(D, D_1, D_2\) and \(D_3\) points of the 5-day coverage curve, denoted by the light-blue line). These points correspond to the \(Q\) values of 14.2, 14.4, 14.5 and 14.6, respectively. Actually, these \(Q\) values represent four RGT orbits with a 5-day repeat cycle, which means that selecting the candidate orbits near the four RGT orbits with a specific repeat cycle can effectively reduce the rolling burden of the satellite. 3) Overlap exists among the coverage curves (e.g., overlap between 3-day coverage curve and 4-day coverage curve denoted by Curve AB), which means that increments of coverage time will not reduce the required observation angle within a certain range of orbital altitude.

5. Conclusion

This paper has applied an ergodic method to systematically investigate global coverage for SSO satellites, which can contribute to providing reasonable reference for the orbit design of remote-sensing satellites. Based on the concept of \(Q\) value, this paper built a bridge connecting revisiting and RGT orbits through the mathematical expression of the nodes’ accessing sequence. Considering the requirements of cameras, this paper gives a global distribution of orbit altitude \(h\) and observation angle \(\gamma\), and the coverage time related to every pair of \((h, \gamma)\), and presents an efficient method that can quickly calculate the coverage percentage within a specific number of days. Through analyzing the influence of transfer errors on the coverage, this paper also provides orbit control thresholds for orbit altitude and attitude control thresholds for increasing the observation angle. The global coverage properties of SSOs were discussed from the following three aspects: 1) The temporal changing trend of cover-
age percentage; 2) the minimal coverage time required for global coverage, which contributes to designing proper orbits based on corresponding mission requirements; and 3) the minimal observation angle required to achieve global coverage.

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