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Influence of Indirect Solar Irradiance on Satellite Observation

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Abstraction

With the development of Space Domain Awareness(SDA), satellites' optical characteristics are becoming attention-grabbing. Sunlight was usually considered the only light source for the satellites. However, in the actual observation, researchers have found that earthshine and moonlight would increase errors of the observation results, which have greatly influence the estimation of the satellite's state. In order to avoid this influence, we propose an observation strategy. Firstly, we propose an accurate earthshine model, which considers the earth's volume and favors long-time continuous satellite observation. Then, we explore the earthshine and moonlight's impact on satellite observation results and find that this impact varies with the satellite attributes. Furthermore, we Figure out the law of this impact and establish a connection between this law and observation geometry. Finally, a Period Contribution model is proposed to provide a corresponding observation strategy to avoid the influence of earthshine and moonlight.

Keywords: Satellite observation, Indirect solar irradiance, Material, reflection, Contribution.

1 Introduction

Ground-based optical observation is an important method for obtaining satellite characteristics. Due to the optical propagation principle and satellites' material properties, the satellites' optical information is primarily determined by the observation geometry (defined as the relative position of the light source, satellite, and detector in this paper) and the optical signal received by detectors will differ with the different shapes, sizes, materials, and working states of the satellite. Referring to it, we can recognize satellites' specific characteristics with the photometric data by observation[1-6]. The sun was usually considered the only light source for satellites in space[7-9]. However, there is more than one light source other than the sun in space, which results in a mixing light consisting of lights at different Incident angles[10]. After reflected by the satellite, the mixing light is received by the detector as the satellite's optical information, which causes a non-negligible error for the satellite estimation (see Fig. 1).

Fig. 1. Multiple light sources influence the satellite observation

As shown in Fig. 1, the primary obtrusive light sources are the moon and the earth[10,11]. Instead of emitting light themselves, they reflect the sunlight to illuminate the satellite, called Indirect Solar Irradiance (ISI)[11-13]. They are different from the stray lights, which interfere with the telescope lens during observation. They affect the observation results by increase the incident lights in different directions to the satellite.

Because sunlight is a parallel light from one point, the moon's and the earth's whole body cannot be illuminated simultaneously, as shown in Fig 1. Indirect Solar Irradiance at the satellite is closely related to the geometric position of the sun, the indirect light sources, and the satellite. Besides, most satellites' shapes and materials are irregular, which causes a close relationship between the optical signal received by the detector and the observation geometry (relative position between the light source, the satellite, and the detector). As a result, for satellite observation, it is necessary to consider the relative position between the sun, the indirect light sources, the satellite, and the detector.

In order to provide a theoretical reference for satellite observers to avoid the influence of Indirect Solar Irradiance at present, we Figure out how Indirect Solar Irradiance can affect the satellite observation and when observers should take the Indirect Solar Irradiance into consideration.

In this paper, observation geometries at different moments are considered. Firstly, an accurate earthshine model is proposed, which divides the earth surface into quantities of slices. This model can simulate the earth's irradiance at the satellite at different moments. Secondly, we obtain photometric information (integral of the spectrum) of multiple light sources and conduct a long-term and continuous satellite observation. Thirdly, a concept of 'Contribution' is proposed to measure each light source's influence on the satellite photometry. The 'Contribution' is defined as the ratio of the irradiance from the satellite caused by a single light source and the total irradiance from the satellite. Afterward, we explore the Contribution of each light source on satellites of different orbits and different materials and find that Indirect Solar Irradiance's Contribution will vary with satellite attributes and orbital attributes. The variation law is explained with the observation geometry. Finally, a Period Contribution model is proposed for the satellite observers to plan the observation time

better. Fig. 2 is the flow chart about each section.

Fig. 2. Flow chart of this paper

2 Related works

With the development of observation technologies and research methods, some unreasonable phenomena have appeared in daily satellite observations. For example, when performing multi-phase optical observations on different satellites, researchers found that the trend of the optical curves at large longitudinal phase angles tends to be gentle[10,14], which means that the influence of earthshine on the satellite is more outstanding than that of the sunlight. Similarly, there is an opposition effect at the large lunar phase angle (defined as the angle between the earth and the sun as viewed from the moon) when observing the moon[15], which interferes with satellite observations in many times.

Recently, researchers have explored the influence on the satellite photometry made by earthshine. Grant M. Thomas *et al.*[11] think earthshine should be considered in the daytime when the satellite is right back to the sun. Whether the solar phase angle (defined as the angle between the sun and the detector viewed from the satellite) is up to 90 deg is the judging condition that the satellite is back to the sun, which determines the sunlight's low impact on satellite photometry. Peter Zimmer *et al.*[13] consider the earth a Lambertian sphere with a constant reflectivity. To explore the earth's irradiance on a low-earth-orbit(LEO) satellite, they performed an additional atmospheric simulation all over northern New Mexico, more precisely showing earthshine from this area to the satellite.

Nevertheless, most researchers' purpose is to explore the feasibility of executing the satellite observation with earthshine in the daytime[10,11,13,14,16,17,18]. They ignore that the earthshine's effect on the satellite photometry is different at different moments due to the observation geometry's change. Besides, a detailed comparison between the earthshine's Contribution and the sunlight's Contribution to satellite photometry has not been given. We need a quantitative standard to determine whether

or not to ignore the earth's irradiance. So far, there is no related research on moonlight.

3 Method

For simulating the satellite observation under different light sources, we construct three irradiance models: Direct Solar Irradiance Model, Lunar Irradiance Model, and Earth's Irradiance Model.

Direct Solar Irradiance Model aims to calculate the solar irradiance at any position. Because the sun is a constant light source, distance is the only variable factor. According to ROLO, the lunar observation database accumulated by the USGS-sponsored project[19], Phan Dao *et al.*[20] have built an improved lunar irradiance model——MT2009, which assumes the moon as a Lambertian sphere and simplifies the opposition effects[21,22] and the libration effects[23]. MT2009 has referred to the previous decades of astronomers' measurements and has high accuracy[24]. In MT2009, the Lunar phase function, a function depending on the lunar phase angle, is defined to describe the non-linear behavior of lunar irradiance related to the lunar phase angle.

Similar to the lunar phase function, researchers have fit the earth's irradiance of different phase angles and given the earth's phase function[12,25,26]. They assume the earth as a point source. However, it is not appropriate because the satellite is much closer to the earth than to the moon, which means the volume of the earth should be considered. To avoid errors caused by this assumption, we divide the earth into quantities of slices. Each slice participates in calculation individually. The atmospheric model is simplified so that our model favors long-time continuous satellite observation.

3.1 Direct Solar Irradiance model

Suppose the average distance between the sun and the earth to be $R_0 = 1.495 \times 10^8 \text{ km}$ [20]. Then the irradiance upon visible light band ($0.4 \sim 0.7 \mu\text{m}$) will be integrated into $Q_0 = 438.894 \text{ W/m}^2$ [27] at the distance of R_0 . And the scenario that the sun is blocked should be excluded. The solar irradiance is inversely proportional to the square of the distance to the sun, so the irradiance of the visible light band of the sun at any position can be expressed as

$$Q = Q_0 \cdot \left(\frac{R_0}{R}\right)^2, \quad (1)$$

where R denotes the distance from the satellite to the sun, Q is the solar irradiance at R .

3.2 Lunar irradiance model

The three scenarios that the satellite can receive the lunar irradiance:

- a) Sunlight can reach the moon, with no obstacle (the earth) between them(i.e., exclude the lunar eclipse, see Fig. 3(a));
- b) There is an overlap between the moon's illuminated area and the visible area on the moon viewed from the satellite (see Fig. 3(b));
- c) Moonlight can reach the satellite surface (see Fig. 3(c)).

Fig. 3. Three situations that moonlight can exactly reach the satellite. (a) The connection between the sun and the moon is tangent to the earth. (b) One of the tangents from the satellite is tangent to the area in the sunlight. (c) The connection between the moon and the satellite is tangent to the earth.

The constraint formulas corresponding to the above three situations are:

$$\begin{aligned}
 \text{a) } \theta_p &> \arcsin\left(\frac{R_E}{R_{em}}\right), \\
 \text{b) } \theta'_p &< \left(\frac{\pi}{2} + \arccos\left(\frac{R_M}{R_{ms}}\right)\right), \\
 \text{c) } \theta''_p &> \arcsin\left(\frac{R_E}{R_{es}}\right),
 \end{aligned} \tag{2}$$

where, θ_p is the angle between the sun and the earth viewed from the moon; θ'_p is the angle between the sun and the satellite viewed from the moon; θ''_p is the angle between the earth and the satellite viewed from the moon. R_{ms} is the distance from the moon to the satellite, R_{es} is the distance from the earth to the satellite, R_{em} is the distance from the moon to the earth, R_M is the moon's radius, R_E is the earth's radius. When the above three constraints are met, it can be considered that the moonlight has an impact on the satellite observation.

We mainly explore the satellite illuminated by the moonlight. Due to the compact contact between the moonlight irradiance and the relative position among the sun, the moon, and the satellite, we define a generalized lunar phase angle θ'_p ($\theta'_p < 180^\circ$). It is acceptable to consider the moon as a point source due to the long distance between the moon and the satellite.

Based on MT2009, we can fit a lunar phase function closely related to the lunar phase angle:

$$f(\theta'_p, \lambda) = 10^{-0.4(a-b\lambda)}, \tag{3}$$

which is applied to the spectral range $[0.3, 1.2 \mu\text{m}]$ ($f \in [0, 1]$). λ is the wavelength, a , b is the fitting parameters related to the lunar phase angle (see in [20]). The equivalent solid angle of the illuminated part of the moon relative to the satellite can be expressed as:

$$\Omega'_m = \Omega_m f(\theta'_p, \lambda) = \frac{\pi R_M^2}{R_{ms}^2}, \tag{4}$$

where Ω_m is the solid angle of the full moon disk relative to the satellite. The equivalent solid angle Ω'_m is the solid angle of the equivalent Lambertian spherical light source calculated referring to the lunar irradiance that the satellite receives.

MT2009 fit the lunar spectral albedo $\alpha(\lambda)$ with various data sources[21,23,28]:

$$\alpha(\lambda) = \sum_{i=0}^n A_i \lambda^i, \quad (5)$$

where A_i is the fitting coefficient linking with the wavelength. The visible light band is most commonly used in daily satellite observation tasks. According to the relationship between the wavelength and the intensity in the solar visible light spectrum, we integrate the lunar albedo of different wavelengths in weight to obtain the average lunar albedo of the visible light band ($\overline{\alpha_m} = 0.116$). The lunar radiance in any direction can be expressed as:

$$L_m = \frac{\overline{\alpha_m} Q_{sm}}{\pi}, \quad (6)$$

where Q_{sm} is the solar irradiance at the lunar surface. According to Equation (1),

$$Q_{sm} = Q_0 \cdot \left(\frac{R_0}{R_{sm}}\right)^2, \quad (7)$$

where R_{sm} is the distance between the sun and the moon. Following is the lunar irradiance at the satellite:

$$Q_{ms} = L_m \Omega'_m = L_m \Omega_m \cdot f(\theta'_p), \quad (8)$$

where Q_{ms} is the lunar irradiance at the satellite.

3.3 Earth's irradiance model

This model divides the earth's surface into small slices according to the latitude and longitude grid (see Fig. 4(a)). Every slice can be treated as a rectangle, the center of which is lied on $(i^\circ E, j^\circ N)$ ($i, j \in N$), and the length and the width of the slice are the distance of one latitude and one longitude, respectively.

Fig. 4. Partition the surface of the earth. (a) Divide the earth's surface into 180×360 slices. (b) Calculation of slices at different positions.

Under the assumption that the earth is a standard sphere, the perimeters of different longitude circles are always equal to $2\pi R_E$. We can get the length of every slice:

$$l_j = 2\pi R_E / 360, \quad (9)$$

where R_E is the earth's radius. Please pay attention that due to the different perimeters of different latitude circles, we should calculate the slices' width relied on their latitude (see Fig. 4(b)). The perimeters of the latitude circles are $2\pi R_E \cos i$ with the latitude i . So, the widths of the slices are

$$d_i = 2\pi R_E \cos i / 360 \quad (10)$$

The slice's area is

$$s_{ij} = l_j d_i \quad (11)$$

Earthshine transfer is studied in two steps. In the first step, the sun illuminates half of the earth's surface. In the second step, the earth's surface illuminates the satellite's surface as a light source. For example, if the slice's center is (i, j) , the precise analysis will be as follows:

Actually, the earth is not orbiting around the sun in a standard circle. In a solar year, as the distance between the sun and the earth is always changing, so is the solar irradiance at the earth, which can be calculated based on the Direct Solar Irradiance model (section 3.1) as:

$$Q_{se} = Q_0 \cdot \left(\frac{R_0}{R_{se}}\right)^2 \quad (12)$$

As shown in Fig. 5, the incident light vector of every slice can be approximated as the sun-to-earth vector $\overrightarrow{SN_{ij}} = \overrightarrow{SE}$ due to the long distance between the sun and the earth. $\overrightarrow{ON_{ij}}$ donates the slice's normal vector (the earth's center to the slice). The slice-to-satellite vector is $\overrightarrow{N_{ij}T} = \overrightarrow{OT} - \overrightarrow{ON_{ij}}$. θ_{in} donates the incident zenith angle and θ_{out} donates the reflection zenith angle.

Fig. 5. Diagram of the slice exposed to radiation

Apart from the ground, the atmosphere covering the ground also has a non-negligible reflex action. According to the middle-earth-orbit (MEO) and the geostationary-earth-orbit (GEO) satellites far from the earth, the area illuminating the satellite is vast, with different climatic regions. The atmosphere varies greatly not only over time but also from region to region, so it is too difficult to simulate the atmosphere in every region. Fortunately, here what we focus on is the total earthshine radiation, so it is acceptable to assume the total average albedo of the ground and the

atmosphere is $\overline{\alpha_e} = 0.3$ [29]. The radiance of the slice in each direction can be expressed as:

$$L_{ij} = \frac{\overline{\alpha_e} Q_{se} \cos \theta_{in}}{\pi}, \quad (13)$$

where $Q_{se} \cos \theta_{in}$ donates the solar irradiance received by the slice. Referring to the Transfer formula from the radiance to the irradiance, the irradiance generated by the slice at the satellite in $\overrightarrow{N_{ij}T}$ can be expressed as:

$$Q_{ij} = L_{ij} \cdot \Omega_{ij} = L_{ij} \cdot \frac{s_{ij} \cos \theta_{out}}{\|\overrightarrow{N_{ij}T}\|^2}, \quad (14)$$

where, $\Omega_{ij} = \frac{s_{ij} \cos \theta_{out}}{\|\overrightarrow{N_{ij}T}\|^2}$ donates slice's solid angle relative to the satellite, s_{ij} donates

the slice (i, j) 's area, $\|\overrightarrow{N_{ij}T}\|$ donates the distance between the slice and the satellite.

Actually, the irradiance at the satellite results from all of the effective slices' joint action.

. We can filter the effective slices by

$$\left\{ \begin{array}{ll} \theta_{in} < \frac{\pi}{2} & \text{(the slice is visible relative to the sun)} \\ \theta_{out} < \frac{\pi}{2} & \text{(the satellite is visible relative to the slice)} \\ \text{There is no obstacle (the moon) between the sun and the earth} & \text{(exclude the solar eclipse)} \end{array} \right.$$

The irradiance at the satellite is the superposition of all of the effective slices:

$$Q_e = \sum_{S_{eff}} Q_{ij}, \quad (15)$$

where S_{eff} donate the effective area. Fig. 6. shows the effective area.

Fig .6. diagram of the effective area. (a) viewed from the side. (b) viewed from the top.

The earthshine from the satellite's visible area can illuminate the satellite. The illuminated area on the earth is the area that the sunlight can reach. The area of the

effective area can be expressed as:

$$S_{\text{eff}} = (\text{illuminated area}) \cap (\text{satellite's visible area}) \quad (16)$$

3.4 Satellite reflection model

Light from the light sources will be reflected by the satellite. Unlike the earth, the satellites' shape is complex and irregular.

During this process, the occlusion relationship between the surfaces for the propagation of the light should be considered, as shown in Fig. 7. the First Occlusion represents that the incident light cannot reach the surface of the target slice due to occlusion, and the Second Occlusion represents that the light reflected by the slice cannot reach the detector due to occlusion. We can determine an invalid slice by any of them, which needs to be eliminated.

Fig. 7. The cases of occluded surfaces. (a) the First Occlusion. (b) the Second Occlusion.

Due to the entirely various shapes of the satellites with too much uncertainty, we simplify the satellite to a cube with a side length of 5m, with every surface being the Lambertian plane, whose radiation is the same in every direction. By doing so, it is easier to reflect the impact of indirect solar radiation to satellite photometry. Fig. 8 illuminates the geometric relationship in the satellite observation. Let the incident light vector (from the sun to the satellite) be λ_s , the observation vector (from the satellite to the detector) be λ_F , and the surface's normal vector be $\mathbf{n}$. Define the angle between λ_s and $\mathbf{n}$ to be the incident zenith angle θ_s and the angle between λ_F and $\mathbf{n}$ to be the observation zenith angle θ_F .

$$\begin{cases} \theta_s = \arccos\left(\frac{-\lambda_s \cdot \mathbf{n}}{\|\lambda_s\| \cdot \|\mathbf{n}\|}\right), & \theta_s \in (0, \frac{\pi}{2}) \\ \theta_F = \arccos\left(\frac{\lambda_F \cdot \mathbf{n}}{\|\lambda_F\| \cdot \|\mathbf{n}\|}\right), & \theta_F \in (0, \frac{\pi}{2}) \end{cases} \quad (17)$$

Fig .8. The geometric relationship among the light source, the satellite, and the detector.

Represent the light source's irradiance at the satellite with Q_{ls} (If the light source is the sun or the moon, it can be regarded as a point source; if the light source is the earth, each slice should be considered a separate light source). The irradiance received by the i_{th} surface of the satellite is

$$Q_{ls}(i) = Q_{ls} \cdot \cos(\theta_s(i)) \quad (18)$$

According to the irradiance transfer formula, the irradiance by the i_{th} surface of the satellite received by the detector is

$$Q_{sf}(i) = \frac{\alpha_i Q_{ls}(i)}{\pi} \cdot \frac{S(i) \cos(\theta_r(i))}{R_{sf}^2}, \quad (19)$$

where α_i donates the i_{th} surface's reflectivity. $S(i)$ donates the i_{th} surface's area. R_{sf} donates the distance between the satellite and the detector. Next is the filter of the effective surfaces of the satellite.

Since the satellite's shape is a convex model, there no need to think about the Second Occlusion. We can describe the First Occlusion by a discriminant coefficient as the following:

$$\eta = \begin{cases} 1, & \theta_i \in (0, \frac{\pi}{2}) \text{ \& } \theta_r \in (0, \frac{\pi}{2}) \\ 0, & \text{else} \end{cases} \quad (20)$$

When the angle between the incident vector and the normal vector is over than $\frac{\pi}{2}$ or

the angle between the observation vector and the normal vector is over than $\frac{\pi}{2}$, we

can determine that there is no light reaching the detector.

Finally, the total irradiance from the satellite to the detector can be expressed as:

$$Q_{sf} = \sum_{i=1}^n Q_{sf}(i) \cdot \eta(i), \quad (21)$$

where n is 6 in this process.

4 Experiments

4.1 Satellite observation under different condition

Based on the model above, we can simulate sunlight, moonlight, earthshine, and the irradiance received by the detector from the satellite. Suppose that the detector is

located at (75.5966°E, 30.0386°N, 0 m). In this simulation, we observe from 1 Jan 2021 00:00:00.000 UTCG to 1 Jan 2022 00:00:00.000 UTCG, by 60s as one step. To explore the celestial irradiance's influence on the photometry of satellites on different orbits and satellites with different materials, we perform two experiments separately as follows.

4.1.1 Observing satellites on different orbits

There are two satellites as the observation targets. One is on the GEO, which is directly above the detector and remains relatively stationary. The other is on the MEO (The orbit altitude is 20000km), maintaining relative motion with the detector. Both of their reflectivity is 0.3. Fig. 9 show the simulation results of the GEO in the form of scattered points.

(a)

(b)

(c)

Fig .9. Simulation results of the GEO. (a) The solar irradiance at the satellite on the GEO during one solar year. (b) The satellite irradiance to the detector caused by the sun. (c) the lunar irradiance at the satellite on the GEO during one solar year. (d) The satellite irradiance to the detector caused by the moon. (e) the earth's irradiance at the satellite on the GEO during one solar year. (f) The satellite irradiance to the detector caused by the earth.

Note that these red points in Fig .9 represents that there is no light reaching the satellite because the light source is blocked.

When observing the satellite on the MEO, we cannot keep them in view because of the relative motion between the satellite and the detector. As a result, we study the accessible arcs only. Fig .10 shows the simulation results on the MEO in the form of scattered points.

(a)

(b)

(c)

(d)

Fig .10. Simulation results of the MEO. (a) The solar irradiance at the satellite on the MEO during one solar year. (b) The satellite irradiance to the detector caused by the sun. (c) the lunar irradiance at the satellite on the MEO during one solar year. (d) The satellite irradiance to the detector caused by the moon. (e) the earth's irradiance at the satellite on the MEO during one solar year. (f) The satellite irradiance to the detector caused by the earth.

Identically, these red points in Fig .10 represents that there is no light reaching the satellite because the light source is blocked. However, the rest of the breakpoints are unobservable due to the fact that the satellite is not visible to the detector.

It can be seen from the Fig.10 that the lower the satellite, the longer the obstruction to the light source. The difference in the satellites' altitude will result in the difference in the irradiance to the satellite. The most influential thing is the satellite photometry, which involves not only the amplitude but also the variation of irradiance with time. In a way, it is necessary to consider the altitude of the satellite when discussing the influence of Indirect Solar Irradiance on the satellite photometry.

4.1.2 Observing the satellite with different materials

To explore the difference caused by different materials, we set each side's reflectivity of the satellite as 0.6, 0.003, 0.15, 0.6, 0.003, 0.15. Fig .11 shows the satellite's attitude. The satellite body axis Z points to the earth center. The X-axis is along the velocity direction. The Y-axis forms a right-handed coordinate system together with X-axis and Z-axis. The red side's reflectivity is 0.6; the blues is 0.003; the yellows is 0.15.

Fig .11. The satellite's attitude relative to the earth

Since the position of the satellite has no change, the irradiance at the satellite won't vary, either. However, the irradiance received by the detector from the satellite may be different. Fig.12 shows the simulation results on different orbits.

(a)

(b)

by Earthshine(GEO, reflectivity differs on each side)

(c)

by Sunlight (MEO, reflectivity differs on each side)

(d)

by Moonlight(MEO, reflectivity differs on each side)

(e)

by Earthshine(MEO, reflectivity differs on each side)

(f)

Fig .12. Simulation results of the different materials. (a) The GEO satellite irradiance to the detector caused by the sun. (b) The GEO satellite irradiance to the detector caused by the moon. (c) The GEO satellite irradiance to the detector caused by the earth. (d) The MEO satellite irradiance to the detector caused by the sun. (e) The MEO satellite irradiance to the detector caused by the moon. (f) The

MEO satellite irradiance to the detector caused by the earth.

Comparing Fig .12 to Fig .10, it can be analyzed that changes in the satellite materials will cause changes in the laws of the satellite photometry changing over time. In addition, the laws' changes differ with different light sources. The earthshine only causes changes in the curve amplitude of the GEO satellite photometry different in the materials, rather than the curve shape. It is because the satellite always faces the earth on the same side, and the detector can receive only this side illuminated by earthshine. In other words, the satellite photometry varies with time in the same way.

The light source's irradiance at the satellite does not refer to the irradiance received by the satellite's surface. Both of the satellites' shape and attitude are not fixed, so the irradiance received by the satellite's surface cannot be determined. Alternatively, it is easy to determine the irradiance at the satellite's position.

According to the solar irradiance at the satellite (see Fig .9(a) and Fig .10(a)), the maximum effect of Direct Solar Irradiance on the satellite photometry should occur at the perihelion (near the original point in the Figure, where the Direct Solar Irradiance comes to the maximum). However, there are biases in Fig .9(b) , Fig .10(b), Fig .12(a), and Fig .12(d). It is because the satellite irradiance received by the detector is not only related to the solar irradiance at the satellite, but also related to the altitude angle and the azimuth angle of the sun and the detector in the satellite system (There are also influence of the satellite shape. Only when the satellite is a Lambertian sphere, it will have nothing to do with these two factors). According to Fig .11, the satellite orbits the earth in a three-axis stable state, so the number and the angle of the sun-illuminated and the observed surface of the satellite are always changing. When the extreme points appear should consider the distance and the geometric relationship at the same time.

Although the solar irradiance is 2~6 orders of magnitude higher than the earth's or the lunar irradiance, it is impossible to keep no matter the GEO or the MEO satellite in the sun all the time. Also, it is impossible to keep the MEO satellite in sight of the detector. Consequently, Indirect Solar Irradiance may dominate the influence on the satellite photometry.

4.2 Analysis of each light source's Contribution

According to the above analysis, we find that each light source's irradiance at the satellite depends on its relative position, which will keep varying over time. We take one solar year as our research time. In order to describe the influence made by each light source easier, it is stated that the proportion of the satellite photometry caused by one single light source to the total satellite photometry is called the Contribution of this light source (η). For example,

$$\eta_{\text{lunar}}(t) = \frac{P_{\text{lunar}}(t)}{P(t)} \times 100\% \quad (22)$$

represents the lunar Contribution to the satellite photometry at this moment. $P_{\text{lunar}}(t)$ donates the lunar irradiance received by the detector, which is transmitted by the satellite. $P(t) = P_{\text{sun}}(t) + P_{\text{earth}}(t) + P_{\text{lunar}}(t)$ donates the total irradiance received by the detector.

Based on the established simulation database, we calculate the Contribution of each light source according to the different orbit altitudes and the different satellite materials, respectively. The results are shown in Fig .13-16.

Fig .13. Contribution of each light source to the GEO satellite with each side's reflectivity being 0.3. (a) Contribution of sunlight. (b) Contribution of earthshine. (c)Contribution of moonlight.

Fig .14. Contribution of each light source to the MEO satellite with each side's reflectivity being 0.3. (a) Contribution of sunlight. (b) Contribution of earthshine. (c)Contribution of moonlight.

Fig .15. Contribution of each light source to the GEO satellite with each side's reflectivity different. (a) Contribution of sunlight. (b) Contribution of earthshine. (c)Contribution of moonlight.

Fig .16. Contribution of each light source to the MEO satellite with each side's reflectivity different. (a) Contribution of sunlight. (b) Contribution of earthshine. (c)Contribution of moonlight.

Compare the Contribution of each light source as shown in Fig .17. The red, yellow and blue points represent the Contribution of sunlight, earthshine and moonlight, respectively.

Fig .17. Comparison of each light source's Contribution. (a) Contribution to the GEO satellite with each side's reflectivity identical. (b) Contribution to the MEO satellite with each side's reflectivity identical. (c) Contribution to the GEO satellite with each side's reflectivity different. (d) Contribution to the MEO satellite with each side's reflectivity different.

It can be concluded from the above Figures that no matter for the GEO or the MEO satellite with the same material on each side, the sunlight's Contribution is always higher than the earthshine's from April to August. However, this regular will change when the materials change. For the GEO, the earthshine's Contribution is higher than the sunlight from March to July. For the MEO, the relative motion between the satellite and the detector on the ground results in the cyclical change in Fig .17(d). So do the Fig .17 (b) partly. For exploring the observation geometry of light sources' Contribution, we have analyzed the representative points of Fig .17(a)(c), as shown in table 1.

Table 1 The observation geometry of light sources' Contribution

Scatter	①	②	③
(X,Y)	(7065000,1) ($\eta_{\text{lunar}}=1$)	(7542000,0.4886) ($\eta_{\text{earth}}=0.4886$)	(17457120,0.5099) ($\eta_{\text{earth}}=0.5099$)
LTCG Time	23 Mar. 23:30:00	29 Mar. 12:00:00	22 Jul. 06:12:00
Q_{sf} by Earth	0	$4.11 \times 10^{-15} \text{ W/m}^2$	$2.07 \times 10^{-15} \text{ W/m}^2$
Q_{sf} by LUNAR	$4.42 \times 10^{-21} \text{ W/m}^2$	0	$2.58 \times 10^{-19} \text{ W/m}^2$
Q_{sf} by Sun	0	$4.30 \times 10^{-15} \text{ W/m}^2$	$1.99 \times 10^{-15} \text{ W/m}^2$

Solar elevation angle(From Satellite)	82.7403 deg	-86.4512 deg	-0.1363 deg
Solar azimuth angle(From Satellite)	-169.4288 deg	-100.2289 deg	-20.2605 deg
Sun-Earth-Sat Angle	172.73 deg	3.55 deg	89.85 deg
Sun-Lunar-Sat Angle	70.72 deg	7.50 deg	33.25 deg
Earth-Sat-Lunar Angle	116.08 deg	7.0830 deg	57.50 deg
Earth-Lunar-Sun Angle	65.12 deg	8.2340 deg	27.90 deg

We can conclude from table 1 as follows:

- The ‘Sun-Earth-Sat Angle’ is 172.73 deg, which means the earth blocks sunlight. So the solar irradiance at the satellite is 0. Meanwhile, the satellite is invisible relative to the earth’s effective area, which means the earth’s irradiance at the satellite is 0. As a result, it is primary to consider the moonlight’s effect.
- The ‘Sun-Earth-Sat Angle’ is 3.55 deg, which means the satellite is between the sun and the earth. At this time, the satellite is strongly reflected by the earth. The ‘Solar Elevation Angle’ is -86.4512 deg, which means the satellite is back to the sun. At this time, sunlight reflected from the back of the satellite cannot reach the detector, inducing the low Contribution of sunlight. However, the lunar irradiance at the satellite is 0 because the ‘Earth-Sat-Lunar Angle’ is too low, which means the earth blocks the satellite so that moonlight cannot reach the satellite.
- The satellite materials differ on each side. We need to think about on which side does the solar incident light. From the satellite’s attitude and material properties in section 4.1, we can know the higher the solar altitude angle, the greater the satellite’s corresponding reflectivity, viewed from the satellite. And it will cause stronger sunlight reflected by the satellite. Besides, the closer the solar azimuth is to 0 deg or 180 deg, the stronger the satellite’s reflection of sunlight. The solar altitude angle is the primary one. However, in this condition, the disadvantage of the ‘Solar Elevation Angle’ will cause a low Contribution of sunlight due to the extreme sensitivity of the satellite photometry to the sun’s relative position changes.

4.3 Observation Strategy

Due to the strong dependence of the satellite photometry on the geometric conditions of the light source, satellite, and detector, we stipulate that the indirect irradiance, whose Contribution is over 0.1, can affect the satellite observation result, which is called the effective indirect irradiance. In order to plan the observation time effectively, we convert the UTCG time used in the simulation to the detector’s local time (+ 5h, according to its longitude). The Period Contribution is defined as the ratio of the effective indirect radiation duration distributed in a period to the total effective indirect radiation duration in a year.

$$\sigma_i = \frac{\psi_i}{\Psi}, \quad (23)$$

where σ_i donates the Contribution of the i th period, ψ_i donates the effective indirect irradiance duration of the i th period, Ψ donates the total effective indirect radiation duration in a year.

4.3.1 Two-hour period Contribution

Divide one day into 12 two-hour periods, and analyze as Fig .18, 19:

Fig .18. Two-hour period Contribution of earthshine. (a) Earthshine illuminates on the GEO satellite with each side's reflectivity identical. (b) Earthshine illuminates on the MEO satellite with each side's reflectivity identical. (c) Earthshine illuminates on the GEO satellite with each side's reflectivity different. (d) Earthshine illuminates on the MEO satellite with each side's reflectivity different.

Fig .19. Two-hour period Contribution of moonlight. (a) Moonlight illuminates on the GEO satellite with each side's reflectivity identical. (b) Moonlight illuminates on the MEO satellite with each side's reflectivity identical. (c) Moonlight illuminates on the GEO satellite with each side's reflectivity different. (d) Moonlight illuminates on the MEO satellite with each side's reflectivity different.

It can be analyzed from Fig .18,19 that the earthshine's influence is mainly concentrated on the 4th~9th two-hour period (local time: 6:00~18:00). For the GEO satellite, the moonlight's influence is mainly concentrated on the 1st and 12th

two-hour period (local time: 22:00~2:00). For the MEO satellite, the moonlight's influence is mainly concentrated on the 1st, 2nd, 11th, and 12th two-hour period (local time: 20:00~4:00).

4.3.2 Date Contribution

We analyze the Contribution from a date perspective as follows:

Fig .20. Date Contribution of earthshine. (a) Earthshine illuminates on the GEO satellite with each side's reflectivity identical. (b) Earthshine illuminates on the MEO satellite with each side's reflectivity identical. (c) Earthshine illuminates on the GEO satellite with each side's reflectivity different. (d) Earthshine illuminates on the MEO satellite with each side's reflectivity different.

Fig .21. Date Contribution of moonlight. (a) Moonlight illuminates on the GEO satellite with each side's reflectivity identical. (b) Moonlight illuminates on the MEO satellite with each side's reflectivity identical. (c) Moonlight illuminates on the GEO satellite with each side's reflectivity different. (d) Moonlight illuminates on the MEO satellite with each side's reflectivity different.

As is shown in Fig 20,21, although the satellite's different altitudes and materials can result in the difference of the Date Contribution, the distribution is even.

4.3.3 Month Contribution

In order to eliminate the influence of ‘Different months have different days,’ we should revise the Month Contribution as follows:

$$\sigma'_i = (\sigma_i / d_i) / (\sum_{j=1}^{12} (\sigma_j / d_j)), \quad (24)$$

where σ_i donates the Contribution of the i th month, d_i donates the days of the i th month, σ'_i donates the revised Month Contribution.

Fig .22. Month Contribution of earthshine. (a) Earthshine illuminates on the GEO satellite with each side’s reflectivity identical. (b) Earthshine illuminates on the MEO satellite with each side’s reflectivity identical. (c) Earthshine illuminates on the GEO satellite with each side’s reflectivity different. (d) Earthshine illuminates on the MEO satellite with each side’s reflectivity different.

Fig .23. Month Contribution of moonlight. (a) Moonlight illuminates on the GEO satellite with each side’s reflectivity identical. (b) Moonlight illuminates on the MEO satellite with each side’s reflectivity identical. (c) Moonlight illuminates on the GEO satellite with each side’s reflectivity different. (d) Moonlight illuminates on the MEO satellite with each side’s reflectivity different.

It can be analyzed from Fig 22, 23 that for the GEO satellite, the moonlight’s influence is mainly concentrated in May and September. For the MEO satellite, the

moonlight's influence is mainly concentrated in May, September, and October. The variety of the satellite's altitude and material will affect the Period Contribution. For moonlight, the Period Contribution will not change with the material changed while the altitude unchanged. Due to the low irradiance of moonlight, only in the period free from sunlight and earthshine can moonlight be effective. Since the orbit does not change, the illumination period of each light source to the satellite will not change. Therefore, the periods of the effective lunar irradiance remain identical. For moonlight, the satellite materials can affect the satellite photometry caused by moonlight rather than the Period Contribution.

5 Conclusion

In this paper, we propose an accurate earthshine model. This model considers the actual volume of the light source, which means the multi-directional incidence of earthshine. Afterward, we establish three irradiance transfer models: solar irradiance model, lunar irradiance model, and satellite reflection model. We have explored different light sources' irradiance at the satellite and the detector's observation during one solar year and analyzed the laws between the observation geometry and the Indirect Solar Irradiance's influence on satellites with different attributes. Moreover, the Period Contributions model is proposed to analyze the primary light source to the satellite observation during different periods. Finally, we provide a specific strategy to avoid the influence made by Indirect Solar Irradiance.

We can conclude that no matter the satellites on different orbits or satellites with different materials, Direct Solar Irradiance is always the primary one. The earth is the primary source of indirect light sources. Due to moonlight's weakness, we need to consider the moonlight only when the satellite cannot receive sunlight or earthshine. The satellite's altitude and material will affect the light source Contribution and the Period Contribution. So, we need to consider both of them when observing in order to avoid Indirect Solar Irradiance. In the future, we can explore more influencing factors of Indirect Solar Irradiance, like the satellite's position relative to the detector, orbital parameters, working status, shape, and attitude, etc.

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