GEO space debris environment determination in the earth fixed coordinate system

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The geostationary (GEO) ring is a valuable orbital region contaminated with an alarming number of space debris. Due to its particular orbital characters, the GEO objects spatial distribution is very susceptible to local longitude regions. Therefore, the local longitude distribution of these objects in the earth fixed coordinate system is much more stable and useful in practical applications than it is in the J2000 inertial coordinate system. In order to describe the GEO objects spatial distribution in different local longitude regions, this paper introduced a new method which can provide the spatial density distribution in the earth fixed coordinate system. Based on two line element (TLE) data provided by the US Space Surveillance Network, the spatial density and flux of cataloged GEO objects are given in the earth fixed coordinate system. Combined with the previous studies of "Cube" collision probability evaluation, the GEO region collision probability in the earth fixed coordinate system is also presented here. The examination reveals that GEO space debris distribution is not uniform by longitude; it is relatively centered about the geopotential wells. The method given in this paper is also suitable for smaller debris in the GEO region.

1 Introduction

The geostationary ring is a valuable orbital region contaminated with an increasing number of space debris. Due to its particular orbital character, the distribution of GEO objects is relatively susceptible to local longitude regions. This information must be considered when preparing to occupy a GEO longitude slot, and it is also critical to forecast the further evolvement of the GEO space debris environment [1].

In existing space debris environment models the spatial resolution is determined in inter coordinates J2000 [2,3,4]. Using various algorithms, the associated spatial density and collision possibilities are given then. Under such concept, longitude is distributed randomly between 0 and 2π. Mean longitude is widely used and spatial density in particular GEO geographic longitude slots cannot be determined. Therefore though average spatial density at GEO region may be estimated with such tools, local intersection events for certain geographic longitude slots are not accessible [5].

In order to overcome this disadvantage, the space debris spatial density and flux in ECEF coordinate system are introduced in this paper, and the collision hazard is also discussed under the same concept. Therefore the spatial density and collision probability at each geographic longitude bin are clearly distinguished without using highly accurate analysis tools. It provides an effective and low-cost way to describe and forecast the GEO space debris environment. Although ECEF frame has been used in the investigations of near-miss events [6], it has not been used in the space

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debris environment models.

The US Space Surveillance Network (SSN) provides a catalog of earth orbiting objects. It nominally includes objects in Low Earth orbit (LEO) greater than 10cm in diameter and lager than 1m in GEO region. Based on 2014/12/10 TLE data [7], the spatial density of cataloged GEO objects are processed in the ECEF coordinate system. Combined with the previous studies of "Cube" collision probability evaluation [3][5], the GEO region collision rate in the ECEF coordinate system is also given in this paper.

The method is also suitable for smaller debris in the GEO region. Currently the longitudinal-dependent analysis is not available in GEO debris environment models such as ORDEM [8] or MASTER [9]. Based our research the further version of space debris environment engineering model SDEEM developed by China will present a longitudinal independent GEO space debris environment description in the ECEF coordinate system.

2 Brief characterization of the GEO objects

2.1 Definition of GEO

According to the Inter-Agency Space Debris Coordination Committee (IADC) space debris mitigation guidelines, the GEO protected region is defined as a segment of spherical space bound in altitude by 200 km below the GEO altitude (35,786 km, the altitude of the GEO earth orbit) to 200 km above the GEO altitude and in latitude by 15 degrees on either side of the equator [10].

This paper mainly analysis cataloged objects on near circular orbits passing crossing the GEO region. The primary source of information is the U.S. Space Surveillance Network (SSN).

2.2 Orbital perturbation in GEO

Due to the non-spherical Earth gravity perturbation, in GEO region where the semimajor axis is about 6.6 times the earth radii, orbit objects are pulled towards two "geopotential wells" by the earth gravitational forces [11,12]. The centers of the geopotential wells are 75 E and 105 W. whether an object is trapped in geopotential wells or not depends on its original longitude and apogee/perigee relative to the GEO arc. There are four categories of GEO objects: trapped east, trapped west, trapped both and drifting. If the objects are trapped east or west, they will continuously oscillate about the center of the well for a long time. For the cases of drifting and trapped between, to complete one full cycle across a geopotential well takes about one to ten years, depending upon the range of the oscillation [1].

2.3 Current situation in GEO

Since 1963 when the first GEO satellite SynCom-2 was launched by America, there have been nearly four hundreds GEO satellites. Due to its orbital characteristics, GEO is a highly valuable orbital region with high traffic [13]. It has become the realm of the satellites mainly focus on communicating, navigation, global positioning, early warning, etc. Fig. 1 shows recent satellites orbits whose period is between 0.9 to 1.1 times of one sidereal day, eccentricity less than 0.2 and inclination less than 30 degrees, which contains most of the objects passing through the GEO region. Fig. 2 shows the distribution of the longitude of these satellites, the longitude bin here is given as 3 degrees. These satellites spend most of their time in the GEO region during their mission, highly affected by the GEO space debris environment.

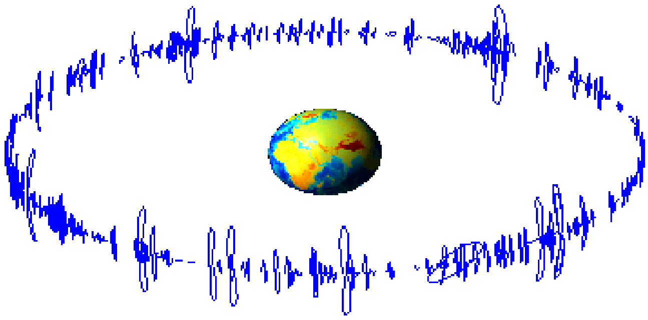

Fig. 1.Orbit tracks of GEO satellites in the ECEF coordinate system

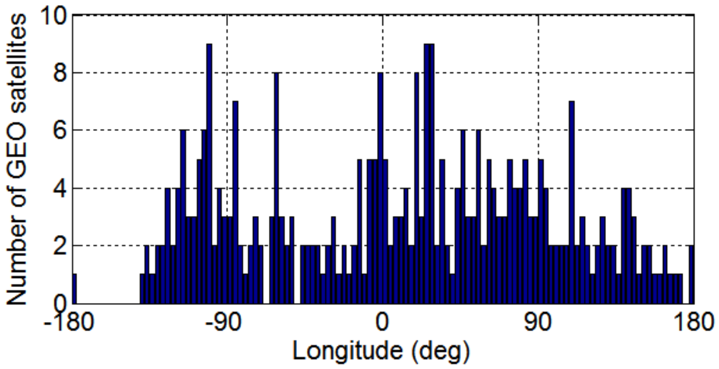

Fig. 2 Distribution of longitude of the satellites in GEO region(1 degree bins)

Considered as one of the most noticeable space environments, orbital debris is a dangerous threat to all human space operations in present and future. It is also seen as a feedback of all kinds of space activities. Current space debris environment models have already considered the GEO region [9][14]. Therefore finding a better way to describe the GEO debris environment is necessary and meaningful for practical applications [6].

By the end of 2014, there were about 983 cataloged objects in the GEO region defined above. There are nearly 2200 objects with diameter between 30cm and 1m currently observed in GEO region, but failed to be cataloged. It is estimated that the number of objects larger than 10 cm would be more than three thousands [1]. The absence of earth atmosphere leads to the lack of natural forces, which cause the objects to decay. Therefore GEO objects' lifetime is more than thousands of years without de-orbiting activities.

Another unique characteristic about the GEO objects is that their longitude positions in the ECEF coordinate system is relatively stable in a couple of days, or even longer. That makes the collision possibilities between the GEO objects are relatively higher in some particular longitude regions, especially the 105 ° W and 75 ° E longitude zones, where the geopotential wells are located. The breakup events would produce feedback effects on the space debris environment. That makes the distribution of GEO objects become more gathered in those particular longitude bins, which can be better described in the ECEF coordinate system than the J2000 coordinate system.

3 Spatial density in the ECEF coordinate system

3.1 GEO objects longitude stability in ECEF coordinate system

Based on previous analysis, it is quite clear that the changing amplitude in longitude in a few days is relatively small compared to the whole 0 to 2π longitude range. In other words, in the ECEF coordinate system, the position of GEO objects is almost stable in longitude; however, in

J2000 coordinate system the orbits of these objects in one day is almost a whole circle surrounding the earth. Two GEO orbits in both coordinate systems are given in figure Fig. 3 and Fig. 4 as an contrast. The inclinations are set as 5 degrees and 15 degrees, the periods are both one day, and the eccentricities are given as 0 and 0.05. The dotted line here represents the imaginary line around the earth parallel to the equator in the GEO region.

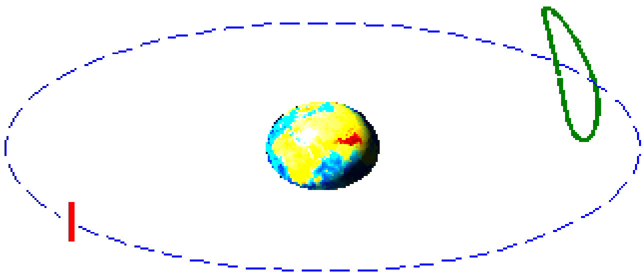

Fig. 3 Two GEO objects orbital tracks in the ECEF coordinate system. The red line and the green line represent each orbital track, the dotted line represents the imaginary line around the earth parallel to the equator in the GEO region.

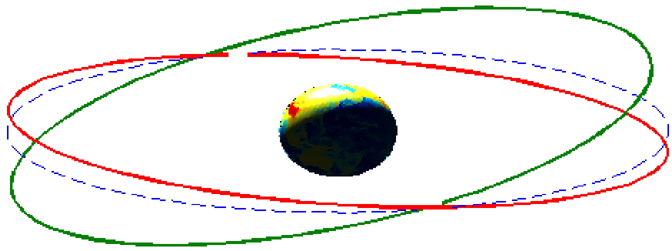

Fig. 4 Two GEO objects in J2000 coordinate system

3.2 Spatial density in ECEF coordinate system

In previous studies, the spatial density is calculated in the J2000 coordinate system. For GEO objects, among all six orbital elements, semi-major axis, inclination, eccentricity，RAAN and argument of perigee always remain unchanged in a few days, but true anomaly moves from zero to almost 360 degrees per period. That makes the spatial density from each GEO objects distributed in nearly all the longitude bins.

Conversely the ECEF coordinate system presents a better way to describe the orbital debris environment. Here we use the mean elements in TLEs as the only input. The algorithm flow of spatial density from one object is given in Fig. 5. M represents mean anomaly, T represents orbital period [15].

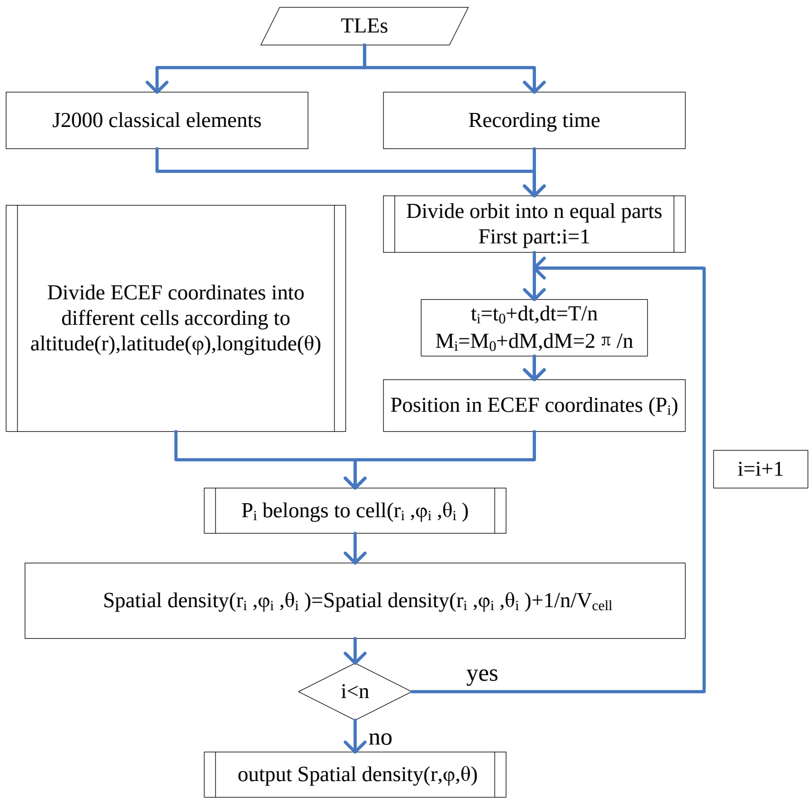

Fig. 5 The algorithm flow of spatial density from one object in ECEF coordinate system

The spatial density in the GEO region from all the cataloged objects is calculated in this chapter. The results are given in Fig. 6. The the longitude bin is defined as one degree. As we can see, the spatial density is relatively higher in the geopotential wells. The result correspond to the actual case, it means the spatial density presented in the ECEF coordinate system proved to be a better way to describe the GEO space debris environment.

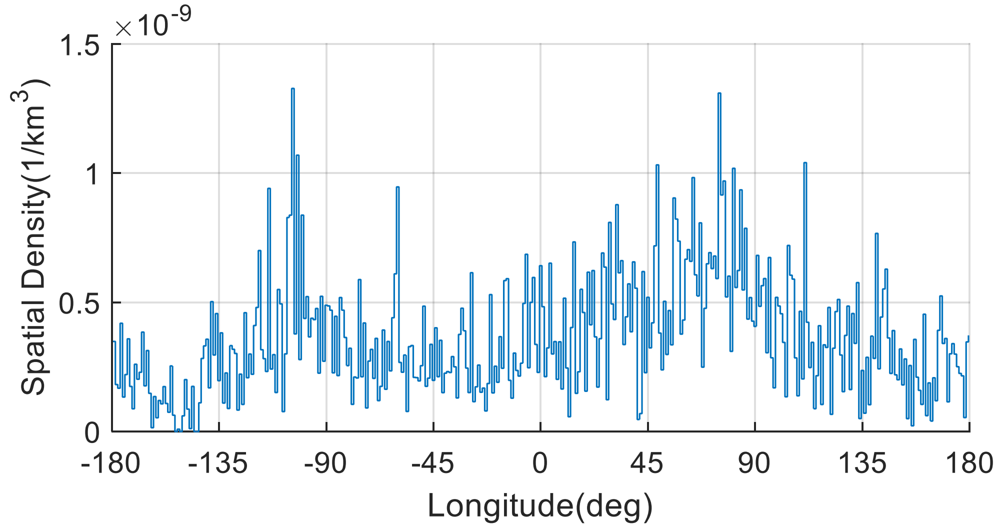

Fig. 6 The spatial density($1/km^3$) in the ECEF coordinate system

4 Collision rate in the GEO region

Nowadays the GEO region has become contaminated with an alarming number of orbital debris, and the collision between them is considered as one of the most important reasons for the accumulation. The analysis of the collision rate in the GEO region is presented in ECEF coordinate system here.

According to Cube Approach method[5], the collision rate between two objects is given as:

$$P_{ij} = s_i s_j V_{imp} \sigma dU \tag{1}$$

$$\sigma = \pi (r_i + r_j)^2 (1 + V_e^2 / V_{imp}^2) \tag{2}$$

$$V_e = \sqrt{\frac{2G(m_i + m_j)}{r_i + r_j}} \tag{3}$$

Here s_i and s_j are the spatial densities from the two objects considered, which can be processed by the previous method given above. r_i and r_j represent average radii of the two objects. dU is the volume of the cube and V_{imp} is the relative velocity between the two objects. σ is the collision cross-sectional area.

Normally cube approach is to apply a clever sampling of objects in time and space during long-term analysis, mostly operate in the J2000 frame. In our paper, we consider the cube is fixed in the ECEF frame, and instead of uniform sampling-in-time, we use actual spatial densities given by the previous discussion. Based on such changements, the collision rate between cataloged objects in GEO region is processed.

The collision rate between cataloged objects in GEO region is presented in Fig. 7. The latitude bin and the longitude bin are both defined as one degree. We can see just as the space density distribution, the collision rate in the geopotential wells is also higher. The result would perfectly sync up with the theoretical idea.

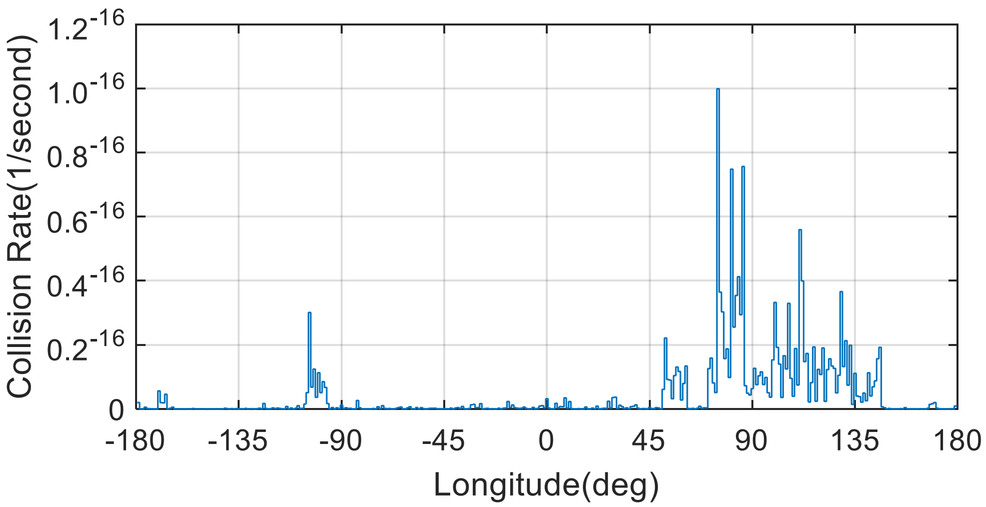

Fig. 7 The collision rate(1/second) in the ECEF coordinate system

The total collision rate over the GEO region is about $7*10^{-14}$ per second. Due to observation imitation, there are hundreds of large objects known to have been released in GEO that are not cataloged. Obviously the collision rate between objects lager than 10cm in diameter would be much larger.

Based upon the research from the kinetic theory of gases, it is assumed that objects are randomly distributed and can all pose a collision risk to each other. The probability of collision

(PC_{ij}) between two objects is given by:

$$PC_{ij} = 1 - \exp(-P_{ij} \times T) \approx P_{ij} \times T \tag{4}$$

T is the time at risk[2].

5 Flux calculation based on local horizontal coordinate system

Flux presents an direct description of impact situation for certain targets. As one of the most important and universal outputs for space debris environment engineering models, flux is widely used to describe the space debris distribution in concerned area. In a certain orbital cell, flux contribution Φ_{j_cell} from a single particle j is given as:

$$\Phi_{j\_cell} = \frac{p_{j\_cell} * p_{tar\_cell} * v_{rel}}{V_{cell}} \tag{5}$$

p_{j_cell} : object density contribution of particle in the cell;

p_{tar_cell} : target residence probability within the cell;

v_{rel} : particle relative velocity (i.e. target velocity with regard to static particle);

V_{cell} : volume of the cell.

In order to present a better description of the flux direction based on earth-fixed coordinate system, earth-fixed local horizontal coordinate system is adopted here [10]. The local horizontal right-handed Cartesian coordinate system can be defined by placing the origin to the earth-fixed local point, x' -axis points in the eastward direction (E), y' -axis points to north (N), z' -axis points to vertical.

For a certain orbital object with semi-major axis a, eccentricity e and inclination i, the velocity in local horizontal coordinate system at geocentric distance r and latitude φ can be written as [16]:

$$v_E = \sqrt{\mu\left(\frac{2}{r} - \frac{1}{a}\right)\frac{a^2\left(1-e^2\right)}{r\left(2a-r\right)}} \times \cos\alpha - \omega_e r \cos\varphi \tag{6}$$

$$v_N = \pm\sqrt{\mu\left(\frac{2}{r} - \frac{1}{a}\right)\frac{a^2\left(1-e^2\right)}{r\left(2a-r\right)}} \times \sqrt{1-\cos^2\alpha} \tag{7}$$

$$v_{z'} = \pm\sqrt{\mu\left(\frac{2}{r} - \frac{1}{a}\right)}\left[1 - \frac{a^2\left(1-e^2\right)}{r\left(2a-r\right)}\right]^{\frac{1}{2}} \tag{8}$$

Where:

$$\cos\alpha = \cos i / \cos\varphi$$

ω_e : the earth's rotation angular velocity.

By definition, if the object is moving towards the earth, $v_{z'} < 0$; otherwise $v_{z'} \geq 0$ .If the object is moving from south to north, $v_N > 0$, otherwise $v_N \leq 0$.

The velocity direction (local azimuth of particle passage A_Φ and local elevation of particle passage h_Φ) of the object with respect to the local horizontal can be given as:

$$A_\Phi = \arctan\frac{v_N}{v_E}$$

$$h_\Phi = \arctan\frac{v_{z'}}{\sqrt{\left(v_E{}^2 + v_N{}^2\right)}}$$

6 Flux in the GEO equatorial region

The equatorial area in GEO region is mostly used for geostationary orbit satellites. Here set the GEO equatorial region as in altitude by 200 km below and above the GEO altitude (35,786 km, the altitude of the GEO earth orbit), and in latitude by 0.5 °on either side of the equator. Fig. 8 and Fig. 9 presented the average flux (in logs) distribution along azimuth in the GEO equatorial region, respectively based on inertially-fixed and earth-fixed coordinate systems.

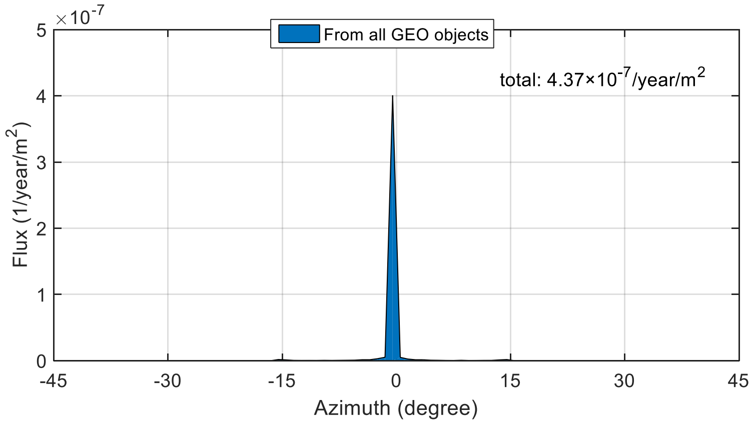

Fig. 8 Flux distribution against local azimuth based on inertially-fixed coordinate system (The total flux from all direction is 4.37×10^{-7} /year/m^2). No flux increase from outside the scope of the azimuth axis.

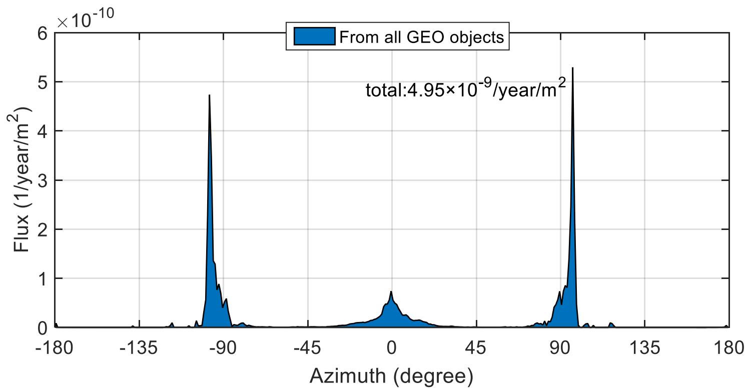

Fig. 9 Flux distribution against local azimuth based on earth-fixed coordinate system

(The total flux from all direction is 4.95×10^{-9} /year/m^2)

Under inertially-fixed coordinate system, almost all GEO objects, the dominate velocity direction is from west to east (the same direction as the earth's rotation), leading to the flux concentration in azimuth around 0°. No object moves in the opposite direction since there is currently no GEO retrograde orbit.

Under earth-fixed coordinate system, flux mainly centralized in two azimuth ranges: (1) the higher priority one, local azimuth close to ±90° (mainly directs northward or southward). (2) lower priority one, local azimuth close to 0° (mainly directs eastward). Further investigation reveals that the inclination distribution of space objects is the key factor that dominates flux azimuth distribution. For all 1372 cataloged objects considered in the calculation, inclination distribution can be divided into two major parts:

Part one, objects with inclination relatively larger. For such objects, the velocity near the equator conforms $|v_N| \gg |v_E|$, $\sqrt{v_N{}^2 + v_E{}^2} \gg |v_z|$. For all 948 cataloged objects with inclination larger than 3°, the average $|v_E|$ is 49.6m/s, the average $|v_N|$ is 484.4m/s, the average $|v_z|$ is 3.0 m/s. Their flux contribution in the GEO equatorial region defined above is given in Fig. 10. The total flux from all direction is 3.38×10^{-9} /year/m^2.

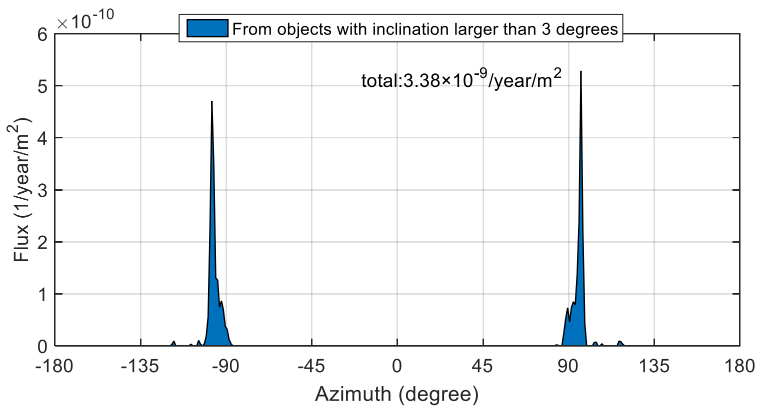

Fig. 10 Flux direction distribution from objects with inclination larger than 3°

Part two, objects with inclination relatively smaller. For such objects, the velocity near the equator conforms $|v_E| \gg |v_N|$, $\sqrt{v_N^2 + v_E^2} \gg |v_z|$. For all 328 cataloged objects with inclination smaller than 0.5°, the average $|v_E|$ is 8.2 m/s, the average $|v_N|$ is 1.5 m/s, the average $|v_z|$ is 0.6m/s. Their flux contribution in the GEO equatorial region defined above is given in Fig. 11. The total flux from all direction is 1.13×10^{-9} /year/m^2.

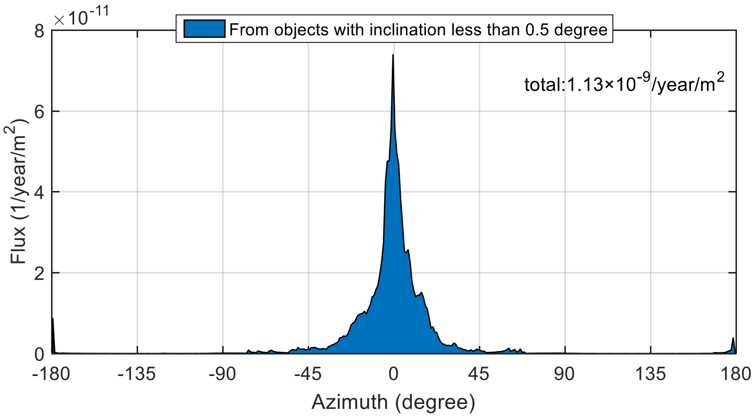

Fig. 11 Flux direction distribution from objects with inclination smaller than 0.5°

7 Equatorial region flux distribution in different longitude areas

It is without doubt that the longitude of certain geostationary satellite is more likely to remain stable during and possible after its mission period. Therefore the investigation of space debris risk assessment in different longitude area is necessary, which is currently inaccessible for GEO debris models developed under inertially-fixed coordinate system. Based on the flux determination method under earth-fixed coordinate system, the flux distribution in different longitude area is discussed here. Divide GEO equatorial region into 360 cells according to longitude. Each cell has longitude range of 1°, altitude range of 35,786±200 km, latitude range of ±0.5°, see Fig. 12. The volume of each cell is about 217 million km^3 and all 360 of such cells comprise the entire GEO equatorial region. Each cell has six surfaces facing different directions.

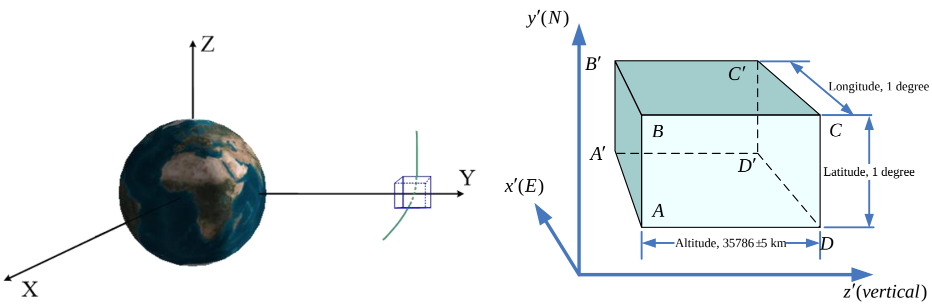

Fig. 12 Divide GEO equatorial region into 360 cells according to longitude

Surface flux against $ABCD$ (facing west) & $A'B'C'D'$ (facing east), $AA'D'D$ (facing south) & $BB'C'C$ (facing north), $ABB'A'$ (facing earth) & $D'C'CD$ (facing sky) is given in Fig. 13, Fig. 14 and Fig. 15. It appears that for most cells defined above, surface flux from south and north side is about three times larger than surface flux from west and east side, making it the dominate source; surface flux from faces towards earth or sky is almost negligible.

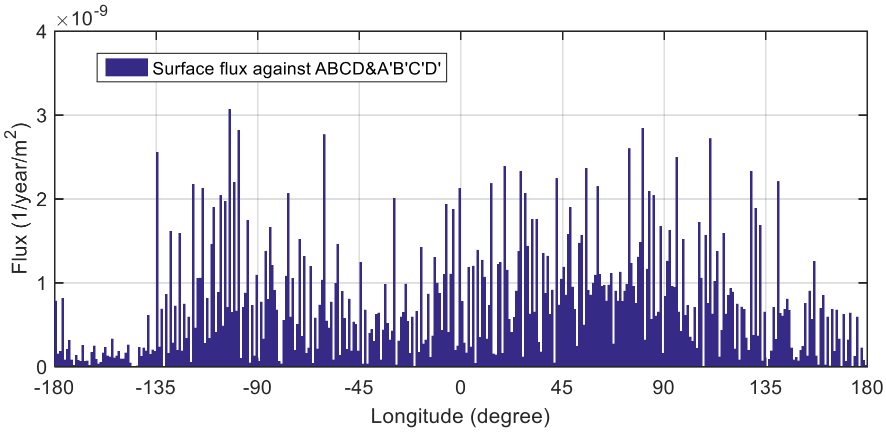

Fig. 13 Surface flux against surface $ABCD$ & $A'B'C'D'$

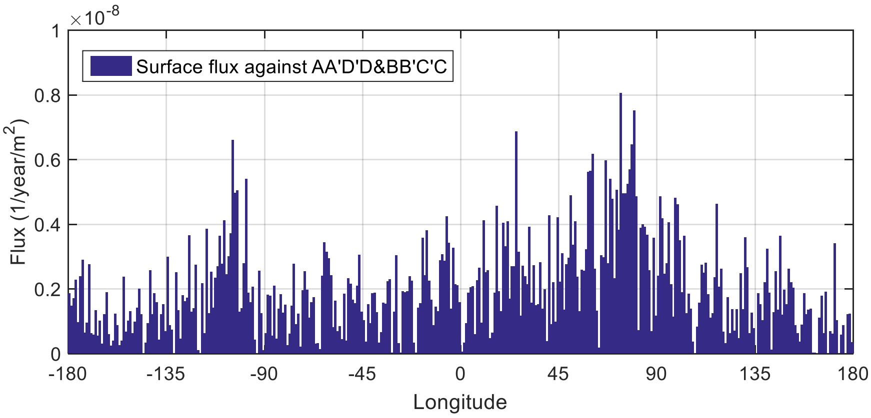

Fig. 14 Surface flux against surface $AA'D'D$ & $BB'C'C$

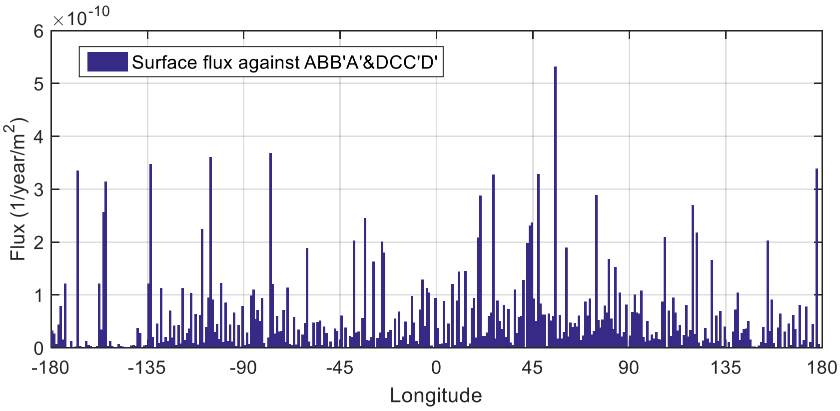

Fig. 15 Surface flux against surface $ABB'A'$ & $D'C'CD$

Average surface flux over all 360 cells from each side of the cells is given in Table. 1. Average surface flux against $ABCD$ is 3 times larger than $A'B'C'D'$, although the average velocity of the latter is much higher. Further investigation reveals that for surface facing west or east, 72.5% of surface flux was contributed from objects with inclination less than 0.5 °. For surface facing south or north, 84.3% of surface flux was contributed from objects with inclination less than 3°.

Table. 1 Average surface flux over all 360 cells from each side

Concerned Surface	Average impact Velocity (m/s)	Average surface flux (1/year/m^2)
$ABCD$ (facing west)	8.3	1.11×10^{-9}
$A'B'C'D'$ (facing east)	50.7	3.6×10^{-10}
$AA'D'D$ (facing south)	27.3	1.94×10^{-9}
$BB'C'C$ (facing north)	28.5	2.04×10^{-9}
$ABB'A'$ (facing earth)	0.82	5.84×10^{-11}
$D'C'CD$ (facing sky)	0.72	5.16×10^{-11}

8 Flux against certain targets

Nowadays, inclined and eccentric geosynchronous orbits are widely used in GEO activities. Previous studies reveal that although the orbital tracks of most GEO objects overlap with each other under inertially-fixed coordinate system, they may never intersect in reality. Only objects entering the same longitude-dependent cells during the time at risk could pose a impact hazard to each other [10]. Based on the flux determination method provided above, impact flux from cataloged objects against such targets is presented here. The orbital elements of the chosen targets are given in Table. 2. Fig. 16 to Fig. 17 presents the flux distribution along local azimuth with respect to the target's orbital velocity coordinate system. The solid lines are given by the algorithm presented in this paper, where the impact flux is obtained based on earth-fixed coordinate system. The dotted lines are given under the concept of current space debris environment models, where the impact flux are obtained based on inertially-fixed coordinate system.

Table. 2 orbital parameters of the two chosen targets

Target parameters	Target1	Target2
Satellite Number	09503	23816
Semi-major axis[km]	42169	42674
Eccentricity	0.0062	0.0065
Geostationary longitude [Degree]	76.52	-1.93
Inclination [Degree]	12.32	2.012
Right Ascension of the Ascending Node [Degree]	65.73	75.21
Argument of Perigee [Degree]	323.16	260.37
Mean Anomaly [Degree]	298.70	315.40

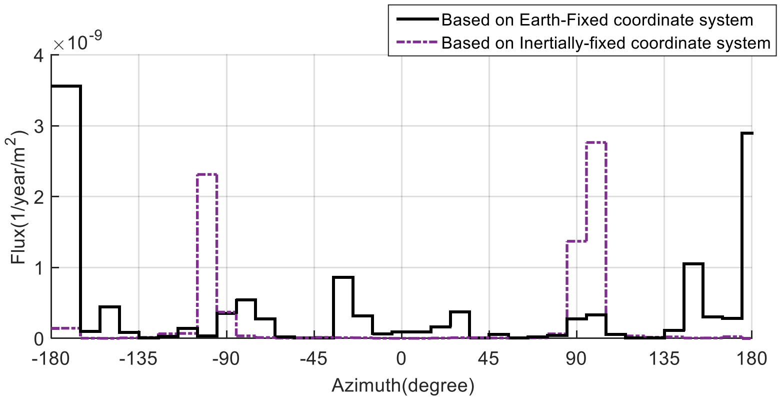

Fig. 16 Target 1: Impact flux distribution along local azimuth

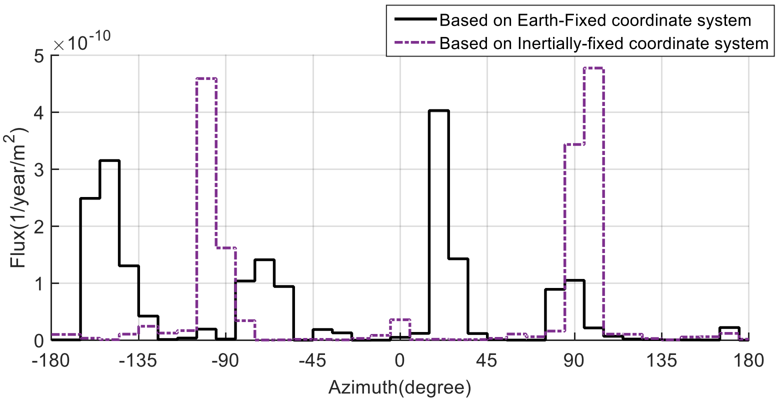

Fig. 17 Target 2: Impact flux distribution along local azimuth

The results show that based on inertially-fixed coordinate system, flux peak occurs around local azimuth ±90° in both cases. This pattern does not apply to the results based on earth-fixed coordinate system. It indicates that the spatial density and residence probability obtained with respect to the earth-fixed local horizontal coordinate system lead to a more accurate flux distribution for targets in GEO region, presenting a reasonable improvement scheme for further version of space debris environment engineering models.

9 Conclusion

The spatial density of cataloged objects in the ECEF coordinate system is performed in the geostationary ring, in order to describe the GEO orbital debris environment in a more accurate method. With publicly-available TLE data, the recent spatial density of the cataloged objects in the GEO region is given in the ECEF coordinate system. The result shows that a considerable number of GEO objects centered near the stable points within the gravitational field, especially the Eastern point. Results of average flux direction distribution based on earth-fixed coordinate system draw to the following conclusions: the flux mainly centralized in two direction zones: the higher prominent one, local azimuth close to ±90° (i.e. the flux directs mainly northward or southward); the lower priority one, local azimuth around 0° (i.e. the flux directs eastward). This pattern also applied to more than half of the particular geographic longitude bins. Near the GEO equatorial plane, surface flux from north & south side is the dominate source. Surface flux from faces towards earth or sky is almost negligible. The comparison of flux determination against certain targets based on earth-fixed coordinate system and inertially-fixed coordinate system shows significant difference. Due to the orbital characteristics of the GEO objects, this distribution is likely to remain stable in a considerable period of time. The spatial density, flux and the resulting collision rate varies significantly by local longitude in the GEO region.

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