Short-term Effect of Intelsat-29e Explosion on GEO Environment

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Abstract. Geosynchronous Orbit (GEO) space environment model of the orbital targets with a size above 10 cm was established according to the amended data and space density. The situation of satellite explosion on GEO is simulated, including the number of fragments generated by the explosion, the size distribution as well as the corresponding mass distribution of the fragments. Under the conditions of selecting fragments of different size for analyzing, the area to mass ratio, discrete velocity, and apogee-perigee distribution can be obtained. By simulating the collisions of targets in different size and mass, and the evolution of the space environment when different size thresholds are selected, the necessity of establishing the GEO space environment and evolution model with the threshold size of 10 cm is demonstrated. The feedback collision caused by the fragments generated by the GEO satellite explosion is simulated under the conditions of different collision probability thresholds. The results show that the explosion fragments would cause a high collision risk environment for other GEO orbital targets, and the risky circumstance would last for hours. The impact of explosive debris on the security of the future space environment is analyzed.

1. Current status of GEO environment
In April 2019, the Intelsat-29e satellite experienced a propellant leak in the GEO orbit and exploded finally, and the resulting debris caused serious hidden dangers to other satellites in the orbit. The GEO orbit is of great importance because of its synchronous nature and the orbit is a very limited resource. The height of the GEO orbit is about 35,786 km. The atmosphere in the orbit is very thin, so there is almost no orbital attenuation in the GEO orbit. Therefore, once the explosion or collision occurs in the orbit, the generated debris will remain in the orbit for a long time, which would increase the risk of secondary collisions and even chain collisions\textsuperscript{[1]}. 

2. GEO Spatial data correction
It is estimated that the number of objects larger than 1 m in the GEO protection area is about 1000, the number of targets with a size between 0.1 and 1 m is about 2,200, and the number of debris whose size larger than 0.01 m exceeds 64000\textsuperscript{[2,3]}. 

According to the orbital elements of the known GEO targets with the size larger than 1 m, the statistical rule of the distribution is obtained. Then the probability density function of each orbital element is generated by multi-peak Gaussian fitting together with polynomial fitting, and the orbital elements of the uncatalogued debris are generated accordingly.
3. Fragmentation Model

The NASA standard fragmentation model can be divided into two parts: explosion fragmentation and collision fragmentation. This article only considers the situations where initial fragmentation condition is an explosion\(^4\).

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Fig. 1. Probability density of semi-major axis distribution.

Fig. 2. Distribution of Eccentricity.

Fig. 3. Distribution of Inclination.

3. Fragmentation Model

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3.1. Fragmentation debris size distribution

First, the feature size \( L_c \) is defined as the average value of the sizes in three axis: 

\[
L_c = \left( \frac{L_x + L_y + L_z}{3} \right)
\]

Cumulative amount distributed of explosion debris whose feature size is greater than a certain \( L_c \):

\[
N(L_c) = 6c_s L_c^{-1.6}
\]  

(1)

Where \( c_s \) is the scaling parameter associated with the type of explosion, and the value is between 0 and 1.

The explosion produces fragments relates to size, which can be seen in Table 1 and Fig.4.

| Size/m | 1   | 0.5 | 0.1 | 0.05 | 0.01 |
|--------|-----|-----|-----|------|------|
| Number | 6   | 18  | 238 | 724  | 9497 |

Fig. 4. Cumulative number relates to size.

3.2. Area to mass ratio distribution

The cross-sectional area “A” of debris can be obtained from the feature size, and the relationship between \( A \) and \( L_c \) shows below:

\[
A = \begin{cases} 
0.540424L_c^2, & L_c < 0.00167m \\
0.556945L_c^{1.984877}, & L_c \geq 0.00167m 
\end{cases}
\]

(2)

Therefore, the mass of debris can be obtained by dividing the cross-sectional area by the area-mass ratio:

\[
m = \frac{A}{A/m}
\]

(3)
Fig. 5. Area to mass ratio distribution of debris above 0.05m.

Fig. 6. Area to mass ratio distribution of debris above 0.1m.

3.3. Separation velocity distribution

The separation velocity direction of the generated debris is an omnidirectional uniform distribution, and the logarithm $\delta=\lg(\Delta v)$ of the separation velocity increment conform to:

$$p(\delta) = \frac{1}{\sigma_\delta \sqrt{2\pi}} \exp \left[ -\frac{(\chi - \mu_\delta)^2}{2\sigma_\delta^2} \right]$$

where $\mu_\delta=0.9\chi + 2.90$, $\sigma_\delta=0.4$.

According to the nature of the single parameter normal distribution, the probability density $p(v)$ is integrated to obtain the probability $P_v$ and therefore:

$$\Delta v = 10^\chi \left[ \mu_\chi + \sigma_\chi \sqrt{2}\text{erf}^{-1} (2P_v - 1) \right]$$

Figure 7 and 8 show the distribution of the apogee and perigee of the explosive debris along with its period. It can be seen from the figure that the orbital period of most fragments is still around 24h. The debris is distributed in an “X” shape. It is seen from the figure, since the original orbital target was running on a near-circular orbit before the explosion, the explosion point would become a perigee or apogee of the explosive debris orbit, that is, neither the perigee or the apogee of the debris is still near 35,786km.
4. Impact Analysis of Fragmentation

4.1. Impact of small targets

According to estimation, the mass of fragments with a characteristic size of 0.1m is about 0.5 kg generally, and the mass of fragments of 0.05 m is about 0.1 kg. In the space collision simulations, the mass of the main target (impacted target) is 6500kg. Under the condition where a debris of 0.05 m collides with the main target on GEO, the collision would not produce any debris larger than 0.05m. When the size of the debris reaches 0.1 m, it turns out this collision would produce fragments whose size may reach 0.1m.

| Conditions | Consequences |
|------------|--------------|
| $m_t$ (kg) | 6500         |
| $m_p$ (kg) | 0.1          |
| $v_t$ (m/s) | 3100         |
| $v_p$ (m/s) | 3400         |
| $L_{min}$ (m) | 0.05         |
| Debris Number | 0 |
| Debris Mass (kg) | 0 |

Fig. 9. Results of colliding with 0.1kg object.
In addition, it is supposed that a satellite explodes on GEO, and then space environment evolution is simulated. If only fragments whose size are larger than 0.1 m are included in research, the evolution is shown in figure, which shows that explosive fragments cause dozens of collision risks, but no fragment is produced during these collision. When the size of fragments in the simulation is set to 0.05 m, the consequence is shown in figure. Contrast to figure, it can be seen that fragments above 0.05 m would cause more collision risks, and longer duration of risks. But the similarity is that no new fragment is generated after the initial explosion, which means no effective collision happen between the explosive fragments and other on-orbit targets.

In the case of only considering whether the collision produces fragments of more than 0.1m and neglecting the damage caused by only small fragments, the space collision simulation software is used, as shown in the figure 9-11, to set the mass of the main target (the impacted target) to 6500kg. Under the condition that the mass is 0.5kg (size 0.1m), this kind of collision will not produce fragments of more than 0.1m, and when the mass from the target reaches 1kg, the collision will produce more than 0.1m of fragments, so the collision is simulated During the process, the minimum size threshold is taken as 0.1m.

Considering the effective collision occurrence and the consideration of the amount of modelling and calculation data, it was decided to carry out the GEO environment evolution with a threshold size of 0.1m.

4.2. Impact of Explode

In terms of geographic longitude, latitude, and height, the GEO region can be divided into hundreds of discrete space units. For each moment, collision probability can be calculated between every two targets in each independent unit. When 0.0001, 0.0002, 0.0003, 0.0004 are respectively taken as threshold values of collision probability, which are reference value of determining whether two neighbouring targets collide or not, the results of evolution can be seen in figure. If threshold value is set to 0.0001, the satellite explosion will bring more than 300 collision risks to the GEO region, and
the duration is maintained for around 90 minutes. In the condition of threshold taken as other values, the risks will be less and duration will be shorter.

Fig. 12. Consequences of probability taken as 0.0001.

Fig. 13. Consequences of probability taken as 0.0002.

Fig. 14. Consequences of probability taken as 0.0003.
Fig. 15. Consequences of probability taken as 0.0004.

It means that, under the current status of GEO environment, a rocket or satellite explosion would cause a circumstance with fairly high collision risk in GEO region, especially for satellites near the explosion point in short term, and the duration of the high risk environment would reach the hour level.

5. Conclusion
Moreover, in the long term, explosive fragments would contribute to a continuous risky circumstance. Once the fragment collides with other targets and generates more fragments, which leads to a riskier circumstance and even vicious circle. Eventually a catastrophic space environment would cause a irreparable and irreversible GEO, with a result that no more satellite can be sent to.

References
[1] D.S. McKnight, F.R. Di Pentino, New insights on the orbital debris collision hazard at GEO, Acta Astronautica 85(2013)73–82.
[2] Space Surveillance Data Available From Joint Space Operations Center, 20 July 2019, (http://www.space-track.org).
[3] ESA’s Annual Space Environment Report 2019, ESA Space Debris Office, 2 May 2019.
[4] Heiner Klinkrad, Space debris: models and risk analysis, Springer, 2006.