



GEO Debris Orbit Determination Method Based on Space-Based Optical Observation

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Abstract. Space debris has a great threat to spacecraft safety. GEO fragments are difficult to measure by laser or radar due to the distance. Using two observation satellites to form a certain observation baseline can be used to determine the orbit of GEO space debris. The feasibility of observation is discussed, the positioning accuracy under different observational geometry conditions is estimated, and the search mode of the observation satellite and the working mode of the observation camera are proposed. For the orbit determination algorithm, the expressions of observations and related partial derivatives are given, and digital simulation of small inclination fragments and large inclination fragments are given. For the fragments with different inclination, the observation time of two satellites is different, the observation time of the small inclination fragments is longer, the geometric conditions are better, and the orbit determination accuracy is also slightly higher.

Keywords: Space debris · Observation of debris · Orbit determination

1 Overview

Space debris poses a great threat to spacecraft safety. Observations of space debris include ground-based radars, ground-based optics, ground-based laser ranging, and space-based optics [1–3]. In order to achieve collision warning of space debris, it is necessary to determine debris orbit. For LEO space debris, radar and laser observations can be used for orbit determination, but GEO debris are difficult to measure due to the distance [4], especially for tiny pieces less than 20 cm. GEO debris can only use ground-based optical observation methods, but the accuracy is poor and the long-term orbit prediction is hard to realize because of less distance information [5, 6]. What's more, ground observations of GEO space debris are limited by weather. A fixed ground observatory can only observe some GEO areas.

Space-based observations of space debris have their special characteristics, and can be used as a complement to ground-based observations. The development of microsatellite technology can also support space-based observations. The spaceborne camera detect debris in a long distance, and has low power consumption and low weight. It not only can be used as a load on GEO microsatellites, but also can be on a large communication satellite to observe fixed areas. Based on single-star optical

observation, only the direction of the debris can be obtained, but the distance can't be obtained. The reason leads to poor positioning accuracy [7, 8]. When the orbit of the space debris is close to the orbit of the observation camera, orbit determination can't even be achieved. It is proposed here that two small optical observation satellites work together and observe the same space debris, so the space debris located at the intersection of the observations in two directions, then the orbit of debris can be determined.

2 Observability and Accuracy Analysis

Two satellites collaborate on optical observation on space debris while measuring the orientation of the target. If the position of the two tracking satellites themselves is more accurate, the two satellites transmit measurement data through the inter-satellite link, and then process the two sets of measurement data on a certain satellite. The distance information of the debris can be calculated geometrically. As shown in Fig. 1, c1 and c2 are two debris observation satellites, the square is the position of the space debris, the angle of the two satellites of c1 and c2 are η which is relative to the target, and the measurement accuracy of the sensor on the satellite c1 is ε , then the accuracy of the estimation of c2 to the target distance is:

$$\delta\rho_2 = \delta\rho_{21} + \delta\rho_{22} = \frac{r_1 \sin \varepsilon}{\sin(\eta + \varepsilon)} + \frac{r_1 \sin \varepsilon}{\sin(\eta - \varepsilon)} \tag{1}$$

$\delta\rho_2$ is the measurement accuracy of c2 to the target distance, and r_1 is the distance from c1 to the target. Considering that the measurement accuracy ε is very small, the above equation can be simplified to

$$\delta\rho_2 = \frac{2r_1\varepsilon}{\sin \eta} \tag{2}$$

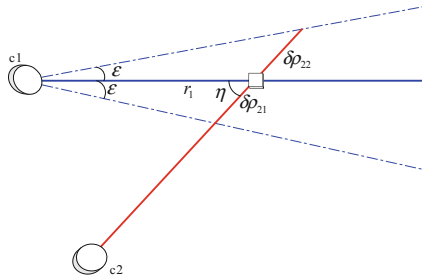


Fig. 1. Geometric relationship of two satellite's observation.

Target position accuracy is related to the geometry between the two tracking satellites and the target. When the angles η are close to 90° , the distance accuracy is the highest.

According to the formula of the estimated accuracy error of the distance, the accuracy of orbit determination using the two-star coordinated measurement is related to three factors:

- Camera angle accuracy ε ;
- The angle η of two tracking stars relative to the target;
- The distance from the tracking satellites to the target.

Therefore, there are three ways to improve the accuracy of collaborative measurement. One is to reduce the measurement error of the sensor, and the other is to select the appropriate observation orbit to make the angle η close to 90° . The third is to reduce the distance from the tracking satellites to the target.

When the two satellites observe cooperatively, two orbits of satellites are 500 km lower than GEO, and the two satellites are 1000 km apart. When the debris on the GEO orbit is directly above the middle of the two satellites, the two satellites simultaneously observe the target. As shown in the Fig. 2, the angle between two sights is 90° , and two satellites are about 707 km away from the target.

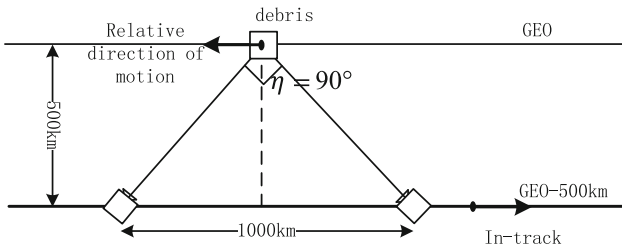


Fig. 2. Optimal observation geometry.

The accuracy of orbit determination is related to position accuracy of the two satellites, the angle accuracy of the camera. Consider the camera angle accuracy is 0.003° , according to (2), the accuracy of the target position is expected to about 37 m. For position accuracy under different observation distances and different observation angles, the relative position accuracy can be divided to two directions, one is vertical to the sight and one is along the sight.

The accuracy which is vertical to the sight is $\delta\rho_{\perp} = \pm r\varepsilon$, r is the relative distance, ε is angle measurement accuracy. The distance estimation accuracy along the sight is the accuracy of the distance estimation $\delta\rho_p = r\varepsilon/\sin \eta$ which is analyzed before, and the positive and negative errors are considered. The estimation formula can also be rewritten as $\delta\rho_p = \sigma r\varepsilon$, the $\sigma = 1/\sin \eta$ is the geometric factor which indicates the magnified relationship of the cooperative observation geometry to the measurement error. As two satellites decrease angle η of the target, the positioning error gradually increases. When the angle η is 30° , the positioning error is doubled.

3 Observation and Orbit Determination

3.1 Search Strategy

In the previous section, the observability and accuracy of space debris location were analyzed under the assumption that two observation satellites simultaneously imaged the same space debris. In actual observation, the location of the space debris is unknown, and it is impossible to align two satellite's observation cameras to the same debris in advance. This requires space debris search on a regular basis, and the search strategy must coordinate with each other.

It is easier to match the observations of two observation satellites, because for one debris, it must be located on a ray from the satellite. If each observation satellite determines a ray, and there is an intersection between the two rays, it means that's the same space debris. Conversely, if there are no intersections between the two rays, it means that two different debris have been observed.

In order to ensure that the two satellites can observe the same debris at the same time, the synchronous area search method which is the reserved search space is meshed, and the two satellites which is according to the synchronous search order, pointing and switching time parameters, point synchronously to the same grid after a certain period time, then switch to the next grid synchronously, and complete the search of the entire search area in turn, is adopted.

Another possible search mode is to use a star-based observation camera to perform spatial search according to certain rules. When space debris is found, obtain the orientation information and track it. Debris will be located on a ray from the satellite. Another satellite searches along this ray. When space debris is found, it judges whether the same target is searched by judging whether or not the two rays have intersection point. After that, two observation satellites can continue to track this space debris.

3.2 Observation Camera Working Mode

Observing the camera in the actual measurement process, there are two ways to measure.

1. The observation camera gives the direction vector of the target in camera coordinate system. Coordinate conversion to the inertial system is performed according to the camera installation orientation, the turntable orientation, and the satellite attitude. At this mode, not only the measurement error of the camera itself, it is also necessary to consider the error during the conversion process.
2. The camera recognizes the background of the sky, while measuring the target. It can directly give the vector of the target in the inertial system. In this observation mode, the measurement error of the target star vector is independent of the error such as the attitude of the satellite and the base coordinate system of the camera. Only related to the accuracy of the camera itself.

The second mode reduces the error transmission link and has higher directional measurement accuracy, but requires the observation camera to have the ability to observe the star at the same time. At present, ground-based telescopes usually perform

debris identification based on the difference between space debris and star imaging features. In ground telescope imaging results, GEO space debris moves at a lower speed and appears as a point on the CCD. The stars appears as a line on the CCD because earth rotation. The lines formed by multiple stars are almost parallel. This method can also be used for observation cameras on the satellite. Using the stars in the image to match, you can get the inertial direction of the observation camera.

3.3 Orbit Determination Method

When two satellites are cooperatively observed, the definition of the vectors is as shown in Fig. 3. The position vector r of the debris is the state to be determined. The observation satellite's position vector r_A and r_B . The satellite's observation is the unit vector z_A and z_B corresponding to ρ_A and ρ_B .

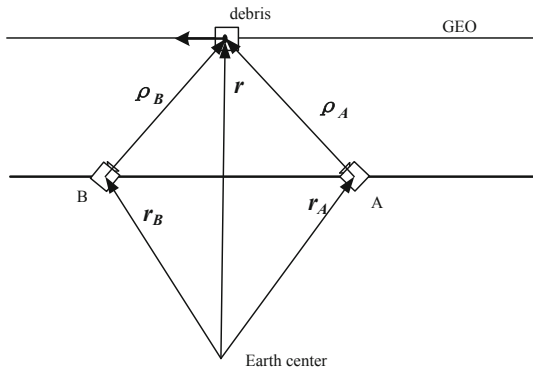


Fig. 3. Geometric relationship of two satellites coordinated observation.

Orbit determination measurement is $z_A = \rho_A / |\rho_A|$ and $z_B = \rho_B / |\rho_B|$, where $\rho_A = r - r_A$, $\rho_B = r - r_B$. The partial derivative of the measurement to the debris position vector r is:

$$H_A = \frac{\partial z_A}{\partial r} = \frac{1}{|\rho_A|} I_{3 \times 3} - \frac{1}{|\rho_A|} (\rho_A \cdot \rho'_A) \tag{3}$$

$$H_B = \frac{\partial z_B}{\partial r} = \frac{1}{|\rho_B|} I_{3 \times 3} - \frac{1}{|\rho_B|} (\rho_B \cdot \rho'_B) \tag{4}$$

With these measurements, the orbit determination of space debris can be completed by Extended Kalman Filter (EKF) or the least squares orbit improvement method.

4 Simulation

Two simulation cases were taken to simulate 0° inclination debris and 15° inclination debris. In the simulation, the observation camera’s measurement error is 0.003° (3σ), and the position error of the two observation satellites is 150 m (3σ). The orbit determination method uses the EKF algorithm. The state variance matrix and the observation variance matrix are diagonal matrix, position state variance is 1×10^{-10} , velocity state variance is 1×10^{-11} , measurement variance is 1.745×10^{-5} . The measuring frequency of the observation camera is 1 Hz, and filtering period is 1 s. In the EKF, the state prediction uses the numerical integration for the position and velocity of the debris.

Simulation case 1: The two observation satellites are 1000 km apart, both in the 500 km under GEO. The two observation satellites move from west to east under the debris, and the two satellites track the target for 5 h. The following Table 1 gives initial orbit elements.

Table 1. Orbit elements in simulation case 1.

Orbital parameter	Debris	Satellite A	Satellite B
a	42164 km	41664 km	41664 km
e	1×10^{-6}	1×10^{-5}	1×10^{-5}
i	0.01°	0.0001°	0.001°
Ω	0°	0°	180°
ω	0°	0°	0°
M	0°	-1.3589°	180°

The simulation results are shown in Fig. 4. Under this simulated orbit condition, the angle η of the two satellite increases from 63° to about 90° , then decreases to 63° . The distance is between 500 km and 1100 km. The steady state position error RMS is 10.3 m and the velocity error RMS is 0.1 m/s.

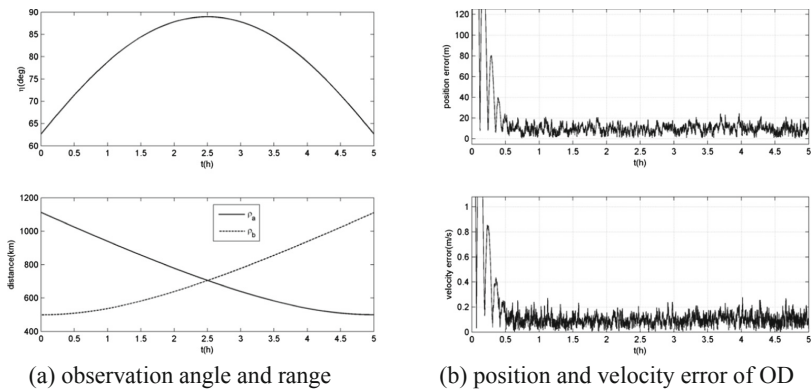


Fig. 4. Orbit determination result for 0° inclination debris

Simulation case 2: Two observation satellites are separated by 1000 km, both in the 500 km under GEO, and the inclination of the debris is 15°. The following Table 2 gives initial orbit elements.

The simulation results are shown in Fig. 5. Under this simulated orbit condition, the observation angle η of the two satellites is increased from 20° to about 90° and then decreases to 20°. The distance between the two observation satellites and the debris is between 500 km and 3000 km. The steady state position error RMS is 15.2 m and the velocity error RMS is 0.11 m/s.

Table 2. Orbit elements in simulation case 2.

Orbit elements	Debris	Satellite A	Satellite B
a	42163.797 km	41663.837 km	41663.817
e	1.47×10^{-5}	1.46×10^{-5}	2.34×10^{-5}
i	15.0°	3.51×10^{-5} °	1.07×10^{-4} °
Ω	2.75×10^{-5} °	12.5462°	179.629°
ω	226.8044°	217.3189°	28.8093°
M	118.1530°	114.2772°	137.0629°

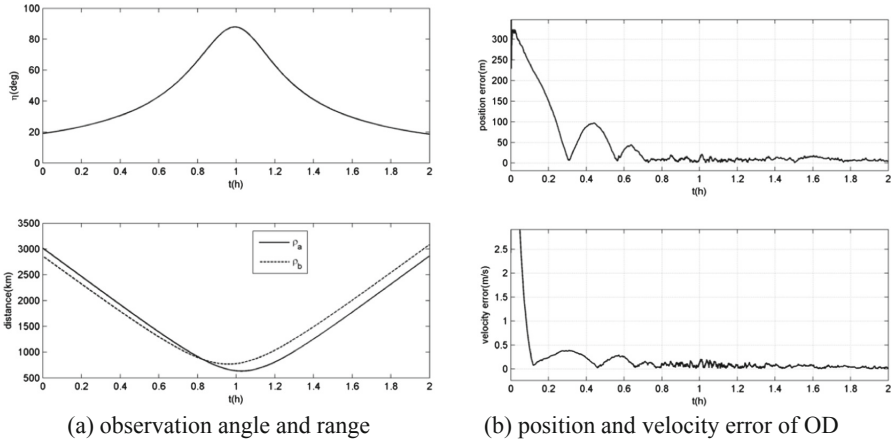


Fig. 5. Orbit determination result for 15° inclination debris.

For debris with 0° inclination, the simulation lasts 5 h, and the observation geometry is better ($\eta > 63^\circ$), so the convergence time is faster and the precision is higher. For debris with 15° inclination, the observation time is only 2 h, and the observed geometric condition η is smaller. Since the η angle changes rapidly, when the η angle becomes rapidly large, orbit determination also converges rapidly, and the positional accuracy is also high. In the process of the debris gradually moving away, the η angle is also reduced quickly.

5 Conclusion

Using two observation satellites to form a certain baseline of observation, the orbit of GEO space debris can be precisely determined. The feasibility of observation is discussed, the positioning accuracy under different observational geometry conditions is estimated, and the search mode of the observation satellite and the working mode of the observation camera are preliminarily proposed.

For the orbit determination algorithm, the expressions of measurement and related partial derivatives are given, and small inclination debris and large inclination debris are digital simulated. For the debris with different inclination angle, the observation time of the two satellites is different. The observation time of the small inclination debris is longer, the geometric conditions are better, and the orbit determination accuracy is also slightly higher. The orbital conditions in the digital simulation are better, and the debris passes just in the middle of the two observation satellites.

In actual flight, the appearance of debris is unpredictable, and the formation configuration of the two observation satellites needs to be optimized for the distribution of space debris. The goal of optimal design is to get better observation conditions for most space debris with the same formation configurations. In addition, in actual observations, the brightness of the debris is related to the angle of sunlight, and the observation camera also needs to avoid sunlight interference. The orbital design of the two observation satellites requires further consideration of various factors such as the direction of the sun and observation geometry.

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