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Orbit determination by genetic algorithm and application to GEO observation

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Abstract

This paper demonstrates an initial orbit determination method that solves the problem by a genetic algorithm using two well-known solutions for the Lambert's problem: universal variable method and Battin method. This paper also suggests an intuitive error evaluation method in terms of rotational angle and orbit shape by separating orbit elements into two groups. As reference orbit, mean orbit elements (original two-lines elements) and osculating orbit elements considering the J2 effect are adopted and compared. Our proposed orbit determination method has been tested with actual optical observations of a geosynchronous spacecraft. It should be noted that this demonstration of the orbit determination is limited to one test case. This observation was conducted during approximately 70 min on 2013/05/15 UT. Our method was compared with the orbit elements propagated by SGP4 using the TLE of the spacecraft. The result indicates that our proposed method had a slightly better performance on estimating orbit shape than Gauss's methods and Escobal's method by 120 km. In addition, the result of the rotational angle is closer to the osculating orbit elements than the mean orbit elements by 0.02°, which supports that the estimated orbit is valid.

Keywords: Initial orbit determination; Genetic algorithm; Optical observation; Lambert's problem; Error evaluation

1. Introduction

Recent space activity is becoming more accelerated, and orbital debris has become an inevitable problem for future space development. Orbital debris includes discarded or artificial objects such as mission-end spacecraft, rocket bodies, and fragments due to explosions or collisions. The orbital debris quarterly news (ODQN, 2013) reveals that there exist approximately 17,000 cataloged objects that are larger than 10 cm in space, and these objects have the possibility of colliding with each other even without human activities in space, which is called Kessler Syndrome (Kessler, 1991). In 2009, a massive destruction was caused by US–Russian satellites conjunction, and more than 2,000 pieces of orbital debris were generated by this accidental collision. ODQN (2013) also stated that this conjunction was the first such event to be observed. It should be noted that there are unobserved small debris in space since the newly confirmed orbital debris are limited to be observable. Moreover, there might be unobserved small collisions as well, so that more attention should be paid to the orbital debris problem.

To deal with the orbital debris problem, orbital debris removal is believed to be essential for sustainable space development and utilization for human beings. Nishida and Kawamoto (2011), Kawamoto et al. (2006), Nishida et al. (2009), and Hirayama et al. (2010) suggested orbital debris removal satellite as one of the solutions. However, it is difficult for any orbital debris removal satellite to approach and catch or grasp a tumbling object. Thus, knowledge on how objects to be removed are tumbling is

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required in terms of orbital debris removal. Such attitude motion can be estimated through light curve, the change of brightness of an object in optical observation.

Currently, Kyushu University (KU) group has aggressively performed research on orbital debris. First, KU developed orbital debris evolutionary model with precise orbit propagator by Hanada and Yasaka (2002) and Narumi et al. (2008). In addition, an effective search strategy applicable for breakup fragments in the geostationary region using ground-based optical observations (Uetsuhara et al., 2012) has been performed. KU has introduced a catadioptric telescope that has the diameter of 16 in., and the focus ratio of F/10 as default. The installed motor driver of the telescope has a high ability enough to track an object in the low Earth orbit as well. By combining the knowledge on the orbital debris motion and the ability of the telescope, it will be possible to estimate attitude motion or shape of orbital debris after establishing the object tracking by the telescope. This light curve inversion techniques, often used for asteroid to estimate attitude motion and shape model (Kaasalainen and Torppa, 2001a,b), will be of great help for the orbital debris removal systems to understand attitude motion from not the space but the ground. KU would like to realize this attitude and shape estimation system using the telescope.

Orbit estimation of orbital debris is required to keep tracking an object and obtain light curves continuously since precise attitude and shape estimation needs several measurement data observed in different geometrical relationship between the Sun, the telescope, and the object with different time. There is no available reference orbit data for the ETS-8 except two-lines element (TLE) from the United States Strategies Command (USSTRATCOM), and the TLEs are known as mean orbit elements, not osculating orbit elements, however. We used the TLE data as the reference although we cannot exclude biases that could be several kilometers. Therefore, it is advantageous and beneficial to estimate the orbit by our own facility. This paper presents a demonstration of orbit determination of geosynchronous satellite EST-8 (International Designator: 06059A, Satellite Number 29656) observed by the telescope at KU, and discussion about the orbit determination error.

2. Observatory at kyushu university

Our Observatory was established at KU in March 2012 to aim at educational use for students (Yamaoka et al., 2013). This observatory is located at the eastern longitude of 130°18′52.8″, the northern latitude of 33°34′12.9″, and the altitude of 72 m. The observatory consists of Meade LX200-Advaced-Coma-Free with the diameter of 16 in., and the focus ratio of F/10. The telescope is equipped with SBIG ST-1001E charge-coupled device (CCD) camera, and the F/3.3 reducer is installed to let the field of view wide to approximately 0.7° by 0.7°. The chip size of the CCD camera is 24.6 by 24.6 mm. The number of pixels is 1024 by 1024. The size of each pixel is 24 by 24 μm.

3. Estimated orbit evaluation method

This section suggests a new method to compare two orbits such as a reference orbit and an estimated orbit from the optical observation. In general, six parameters are needed to represent the orbit such as position and velocity, or Keplerian orbit elements; semi-major axis, eccentricity, inclination, argument of perigee, right ascension of the ascending node, and mean anomaly. The former is advantageous when the orbit is plotted to visually see the difference of position between the reference orbit and estimated orbit. However, even if the positions of the reference and the estimated one are close enough to regard two as the same position, it does not mean that the two orbits are close enough because comparison of velocities is not included yet. The comparison of velocities is difficult to imagine since a threshold of comparison of velocities to judge they are same is uncertain. When comparing Keplerian orbital elements, it is not sure that the thresholds of six orbital elements to define two orbits are close enough.

Our new proposed method separates orbital elements into two groups. The first group includes inclination, argument of perigee, right ascension of the ascending node, and mean anomaly. The second group includes semi-major axis and eccentricity. Then, two parameters will be obtained by following procedures. The first procedure is to acquire an angular difference of rotation matrix derived from the first group of the estimated orbit elements and the reference orbit element. This rotation matrix can be calculated using inclination i, argument of perigee ω, right ascension of the ascending node Ω, and mean anomaly M. First, rotation about third axis is performed by Ω. Next, rotation about first axis is performed by i. Finally, rotation about third axis is performed by $u = \omega + M$. Consequently, the rotation matrix may become:

$$C = \begin{bmatrix} \cos u \cos \Omega - \sin u \sin \Omega \cos i & \cos u \sin \Omega + \sin u \cos \Omega \cos i & \sin u \sin i \\ -\sin u \cos \Omega - \cos u \sin \Omega \cos i & -\sin u \sin \Omega + \cos u \cos \Omega \cos i & \cos u \sin i \\ \sin \Omega \sin i & -\cos \Omega \sin i & \cos i \end{bmatrix} \quad (1)$$

Eq. (1) can be also expressed by Eq. (2) using quaternions. Eq. (2) is commonly used for attitude dynamics to express attitude motion from a reference frame to an arbitrary frame. Parameters q_1, q_2, and q_3, represent rotational axis components, and the parameter q_4 represents the angular component.

$$C = \begin{bmatrix} 2(q_1^2 + q_4^2) - 1 & 2(q_1 q_2 + q_3 q_4) & 2(q_1 q_3 - q_2 q_4) \\ 2(q_1 q_2 - q_3 q_4) & 2(q_2^2 + q_4^2) - 1 & 2(q_1 q_2 + q_1 q_4) \\ 2(q_1 q_3 - q_2 q_4) & 2(q_2 q_3 - q_1 q_4) & 2(q_3^2 + q_4^2) - 1 \end{bmatrix} \quad (2)$$

Both of the reference orbit and the estimated orbit give a rotation matrix using Eq. (1), and each of the rotation matrices can be converted into quaternions-based expression by Eq. (2). In the end, two sets of quaternions