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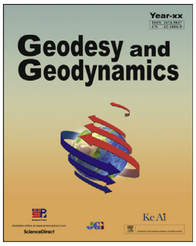

Thermospheric mass density measurement from precise orbit ephemeris

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ABSTRACT

Atmospheric drag, which can be inferred from orbit information of low-Earth orbiting (LEO) satellites, provides a direct means of measuring mass density. The temporal resolution of derived mass density could be in the range from minutes to days, depending on the precision of the satellite orbit data. This paper presents two methods potentially being able to estimate thermosphere mass density from precise obit ephemeris with high temporal resolution. One method is based on the drag perturbation equation of the semi-major axis and the temporal resolution of retrieved density could be 150 s for CHAMP satellite. Another method generates corrections to densities computed from a baseline density model through a Kalman filter orbit drag coefficient determination (KFOD) process and the temporal resolution of derived density could be as high as 30 s for CHAMP satellite. The densities estimated from these two methods are compared with densities obtained from accelerometer data of CHAMP satellite. When the accelerometer data based densities are used as reference values, the mean relative accuracy of the densities derived from precision orbit data using the two methods is within approximately 10%. An application of the derived densities shows that the derived densities can reduce orbit predication errors.

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1. Introduction

Un-modeled atmospheric mass density variations can greatly influence the orbit determination process and add hundreds, even kilometers, of error to orbit predication. Leonard et al. [1] showed that a small tidal variation in the thermospheric mass density can result in in-track prediction uncertainty of order 200 ± 100 m for satellites in about 400 km circular orbits and 15 ± 10 km for satellites in 200 km

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circular orbits for a 24-h prediction. Emmert et al. [2] developed analytical approximations of how mass density uncertainty was projected onto conjunction frequency and found a result, the estimated conjunction frequency was 8 per day, due to the uncertainty of the mass density. For simplicity, we use "density" to refer to mass density (in contrast to number density), unless otherwise noted.

Since the early 1950s various atmospheric models have been developed for estimating the thermosphere parameters, such as density. These models can be classified into empirical and physics-based models. Physics-based models, also known as global circulation models, are not commonly used for orbit propagation and determination due to computationally inefficient. But it is worth pointing out that some physical models are very effective in density calculation. For example, Solomon et al., 2013 showed the TIEGCM can provide excellent agreement with satellite drag observations [3].

The alternative to the physics-based models are the empirical atmospheric models. Typical empirical atmospheric density models, such as the Jacchia series, MSIS series and DTM series models, have errors on the order of 15% one standard deviation [4]. After calibrating the scale of the NRLMSISE00 model using only two line element (TLE) data, the relative root mean square (RMS) error of the model can be reduced by about 9% with altitudes ranging from 200 to 500 km [5]. More calibration methods and corrected models can be found in references [6–9].

Developing high resolution atmospheric models is extremely difficult and it is still far from satisfaction. The density with good spatial and temporal resolutions is a critical requirement for such a development [10]. Picone et al. [11] and Doornbos et al. [7] present methods for retrieving the total density of the upper atmosphere from TLE data of objects in LEO. The temporal resolution is typically hours to days, depending on the precision of the measured trajectory from the TLE data.

Another technique for measuring thermospheric density is using satellites with accelerometers to measure non-conservative forces, which can then be used to retrieve density. The high temporal resolution and high precision of accelerometer measurements are a considerable advantage. Several groups have shown this advantage and derived density from accelerometers with temporal resolution higher than a minute [12–15]. However, only a few LEO satellites are equipped with accelerometers thus that the time span and space coverage of the data are likely not sufficient for developing a model that should be accurate for the whole LEO region and over a long time. Sang et al. [16] and McLaughlin et al. [17] using different methods derived densities with temporal resolution in minutes from precise orbit ephemeris of Challenging Mini Satellite Payload (CHAMP) satellite. These densities are shown well agreed with the accelerometer derived densities along the CHAMP orbit.

An alternative method to that in reference [17] is presented in this paper. This method uses a Kalman filter to estimate the drag coefficient from known precise orbit data, which is available for many LEO satellites carrying global navigation satellite system (GNSS) receivers or laser retroreflectors, for example, the GRACE satellites. The accuracy of these satellites' orbit positions is in the range of a few centimeters to a few decimeters. The precise position data of some satellites is openly available, such as that of CHAMP and GRACE satellites.

In the following, the drag perturbation equation of the semi-major axis is discussed first for better understanding the technique of retrieving thermospheric density from orbit position data. Then the Kalman filter based method to estimate drag coefficient, which can be converted to density estimate, is presented. The method is tested using precise orbit ephemeris of CHAMP satellite, downloaded from the GFZ-ISDC (German Research Centre for Geosciences – Information System and Data Center) website, and the results are compared to the densities derived from the accelerometer data derived densities and those using the method in reference [16]. An application of the derived densities to calibrating an atmospheric density model for improved orbit predication accuracy is shown to demonstrate the effectiveness of the method. Some conclusions and future work plan are given at the end of this paper.

2. Methods of estimating density from precise orbit data

In this section, we present two methods of measuring thermospheric density from orbit data. One is based on the drag perturbation equation of the semi-major axis which relates the change rate of the semi-major axis to the thermospheric density. This method was detailed in reference [16] and a simple description is given here. The other method uses a Kalman filter based orbit determination procedure to estimate the drag coefficient along with the position and velocity of the satellite, where the orbit data is used as observations input to the Kalman filter. The estimates are optimal in the frame of the minimum variance estimate or least-squares.

2.1. *Density estimation using drag perturbation equation of semi-major axis*

Atmospheric drag affects the orbit motion of a LEO satellite. If the satellite orbit positions are determined, such as by the kinematic positioning using onboard GNSS data, then the orbit perturbation due to the drag can be estimated after removing other perturbation effects. From the drag-induced orbit perturbation, the thermospheric density ρ can then be estimated using the equation:

$$\rho = -\frac{\mathrm{d}a}{\mathrm{d}t} \Bigg/ \left(B v_r^2 \frac{\sqrt{1+e^2+2e\cos f}}{n\sqrt{1-e^2}} \right) \tag{1}$$

where B is ballistic coefficient, v_r is the satellite velocity relative to the atmosphere, e is the orbit eccentricity, f is true anomaly, n is mean motion, $\frac{\mathrm{d}a}{\mathrm{d}t}$ is change rate of the semi-major axis caused by drag. The approximate value of change rate of the semi-major axis caused by drag can be estimated using:

$$\frac{\mathrm{d}a}{\mathrm{d}t} = \frac{a_f - a_t}{t_1 - t_0} \tag{2}$$

where a_f is drag-free semi-major axis which can be obtained by the techniques of precise numerical orbit integration