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Calibrating the scale of the NRLMSISE00 model during solar maximum using the two line elements dataset

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Abstract

Empirical mass density models for the thermosphere are widely used for object orbit determination and prediction, object collision avoidance, and re-entry analysis. But the error of these empirical models can often reach 15–30% or even larger during highly disturbed periods of the space environment. On the other hand, the mass density of the thermosphere can be derived from the orbit information contained in the two line elements (TLE) dataset. This technique provides an approach for calibrating the empirical model. Here we select TLE data of 36 low Earth orbiters (LEOs) recorded during 2000–2002 (solar maximum). The ratios of the TLE-derived densities to those from the empirical NRLMSISE00 model are calculated and used to calibrate the scale error of the NRLMSISE00 model by applying a linear height-dependent function. The calibration models for the NRLMSISE00 model during 2000–2002 are then obtained by a least squares adjustment procedure. The calibration factors at 250, 400, and 550 km from this calibration model are compared to the density ratios obtained by Emmert et al. (2008) who used TLE data from ~5000 LEOs. The result indicates that the biases between these two independent factors at the 3 altitudes are all within +/−2%, and the standard deviations (STDs) are under 7%. Another 5 LEOs with altitudes ranging from 200 to 500 km are also selected to validate the precision of the calibration model. Their density ratios are calculated using the calibration model and the NRLMSISE00 model, respectively. The results demonstrate that by applying this calibration method the relative root mean square (RMS) error of the NRLMSISE00 model can be reduced by about 9%.

Keywords: Thermosphere mass density; Model calibration; NRLMSISE00; Two line elements; Scale factor; Solar maximum

1. Introduction

The thermosphere extends from about 90 km to between 500 and 1000 km above the Earth's surface. Driven by solar and geomagnetic activities, the thermosphere density varies considerably in both spatial and temporal domains, which makes it difficult to model and predict the density. Empirical models for the thermosphere density such as Jacchia (Jacchia, 1977), DTM (Barlier et al., 1978; Berger et al., 1998; Bruinsma et al., 2003, 2012), and MSISE (Hedin et al., 1977; Picone et al., 2002) have been widely adopted to determine and predict the orbits for low Earth orbiters (LEOs), as well as life time, re-entry analysis, and others. Currently the error of these models can be as large as 15–30%, and during highly disturbed periods of the space environment due to solar flares, geomagnetic storm, or other strong activities, the errors can become even larger (Marcos et al., 2006).

Many studies have been carried out to improve the precision of the empirical density models, and two strategies have been proposed to reduce the modeling errors. One is to use the more accurate proxies and indices such as E10.7, S10, and MG II for a better interpretation of the

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solar and geomagnetic activities (Bowman et al., 2008; Storz et al., 2005; Tobiska et al., 2008). The other approach is to combine different types of measurements of the thermosphere density to improve the empirical models. The first method often requires modifying the existing models or building a completely new model. In comparison, the latter method can improve the model precision by re-estimating the model coefficients.

In the US-Russian collaborative density calibration project, an altitude-dependent linear model was developed to calibrate the empirical GOST and NRLMSISE00 models by using the TLE dataset (Cefola et al., 2004; Yurasov et al., 2006). The precision of the calibration model was also evaluated by LEO orbit prediction with and without the calibration model. The results indicated that the calibration model can improve the prediction precision for a short time, but it has no significant improvement over a period longer than several days (Yurasov et al., 2006). The HASDM (High-Accuracy Satellite Drag Model) project conducted by the US Air Force Space Command provided another way for empirical model calibration. By using the radar tracking observations from the SSN (Space Surveillance Network), the orbits of 75–80 LEOs and the coefficients of the Jacchia-70 model were estimated simultaneously. The solar radiation and geomagnetic indices generated by the SOLAR2000 model were also used because of their superior accuracies. The results showed that the Bowman method can reduce the density model error to 6–8% at the altitude of 200–800 km, and the drag-induced orbit prediction error by using this model can be decreased by 40% (Bowman and Storz, 2002; Storz et al., 2005).

However, neither the HASDM model nor the SSN data are publicly accessible. Emmert et al. (2004) and Picone et al. (2005) proposed a new method for deriving the thermosphere density using the TLE dataset (Emmert et al., 2004; Picone et al., 2005). By deducing the partial equation of the effect of the non-conservative force on an object's mean motion change Δn_M, the velocity-weighted average density along the object's trajectory over the integration time can be derived using the n_M data provided by the TLE. This provides a new approach for calibrating the empirical model for the thermosphere density, since the TLE-derived densities can serve as measurements for calibration. Doornbos et al. (2008) studied the thermosphere density calibration using the TLE-derived density from about 50 LEOs during the year 2000. The temperature parameters of the empirical CIRA model were re-estimated each day by using the TLE-derived densities as measurements. And by using the ratios of the TLE-derived densities to the densities from empirical models, the calibration factors were also estimated as spherical harmonics of the local solar time and the latitude at different altitudes. The results showed that both of these two calibration methods can reduce the error of the CIRA and NRLMSISE00 model from 25–30% to under 12% (Doornbos et al., 2008).

Our paper first introduced the method of retrieving the thermosphere density from the TLE dataset. Based on this, an altitude-dependent linear calibration model was established using 36 LEOs' density ratios during 2000–2002. The coefficients of the calibration model were estimated each day and the calibration factors at different altitudes were compared to previous studies. We also selected another 5 objects to independently test the accuracy of the calibration model. And the results were compared to those from Doornbos et al. (2008).

2. Data and methodology

2.1. Data description

The TLE ephemeris is distributed by the US Strategic Command, consisting of the mean Keplerian orbital elements and the reference epoch information. The TLE are obtained by fitting the SSN observations using the SGP4 (Simplified General Perturbations) propagator, which is a fully analytical propagator that uses a differential correction technique and fits the radar tracking observations to determine the orbit (Vallado and Crawford, 2008). The orbit precision derived directly from TLE is typically on the order of a kilometer, while the velocity is often at the m/s level. The Space Object Catalog contains TLE records of more than 29,000 objects, and this TLE dataset continues to update until object re-entry. The history of TLE data of some tracking objects can be as long as 40–50 years, which provides plenty of data for studying the thermosphere density from the objects' orbital evolutions.

In the SPG4 implementation, the periodic variations due to the gravity perturbations are averaged to produce mean values of the orbital elements. So when recovering the osculating state vector from the TLE ephemeris, the SGP4 program should be adopted to reconstruct the periodic variations. In the fitting process the contaminating perturbations due to the Earth's gravity field are removed. This leaves only the drag and solar radiation pressure (SRP) responsible for the change in the mean semi-major axis Δa_M. For LEOs with altitudes less than 800 km, the drag is the main non-conservative perturbation and the SRP is negligible. Because the a_M can be directly computed from the TLE mean motion n_M, the Δa_M information inferred from the TLE data can be employed for deriving the thermosphere mass density.

2.2. Methodology

2.2.1. Derivation of the thermosphere density from TLE dataset

As demonstrated above, only drag and SRP are responsible for Δa_M computed from TLE. Based on the perturbation equations, the partial equation of a_M over time can be expressed below (King-Hele, 1987):