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Mean thermospheric density estimation derived from satellite constellations

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Abstract

This paper defines a method to estimate the mean neutral density of the thermosphere given many satellites of the same form factor travelling in similar regions of space. A priori information to the estimation scheme include ranging measurements and a general knowledge of the onboard ADACS, although precise measurements are not required for the latter. The estimation procedure seeks to utilize order statistics to estimate the probability of the minimum drag coefficient achievable, and amalgamating all measurements across multiple time periods allows estimation of the probability density of the ballistic factor itself. The model does not depend on prior models of the atmosphere; instead we require estimation of the minimum achievable drag coefficient which is based upon physics models of simple shapes in free molecular flow. From the statistics of the minimum, error statistics on the estimated atmospheric density can be calculated. Barring measurement errors from the ranging procedure itself, it is shown that with a constellation of 10 satellites, we can achieve a standard deviation of roughly 4% on the estimated mean neutral density. As more satellites are added to the constellation, the result converges towards the lower limit of the achievable drag coefficient, and accuracy becomes limited by the quality of the ranging measurements and the probability of the accommodation coefficient. Comparisons are made to existing atmospheric models such as NRLMSISE-00 and JB2006.

Keywords: Thermosphere density; Satellite drag; Two-line elements; Constellation

1. Introduction

Atmospheric drag and gravity are the predominant forces acting on satellites in Low Earth Orbit (LEO). Satellites under the influence of drag caused by the atmospheric neutral density will gradually decay in altitude over time as well as undergo orbit changes. Hence, the modeling and prediction of this phenomenon is essential to the astrodynamics community, as it helps predict and maintain satellite orbits, aids conjunction analysis and promotes our understanding of Earth's atmosphere under solar influences.

Atmospheric density is a spatially and temporally varying phenomenon. An example of a spatial variation occurs when a satellite passes over the equator versus when it passes over the poles. Temporal variations of density are more difficult to characterize and are often linked with solar conditions: it varies diurnally (due to the day/night cycle), monthly (due to the Sun's rotational period), seasonally (varying distance from the Earth to the Sun as well as changing position of the sub-solar point), and every 11 years (due to the solar sunspot cycle) (Vallado, 2013, 553–555). All of these factors create a complex system that is difficult to model.

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Modeling the atmospheric density has been an ongoing endeavor for the past 50 years. One of the more widely used models is the Jacchia series (Jacchia, 1965, 1970), which initially starts as a model of atmospheric temperature. Corrections have been made based upon empirical data from satellite orbits with the latest iteration being Jacchia-Bowman 2008, or JB2008 (Bowman et al., 2008b,a). Another commonly used model is the Mass Spectrometer and Incoherent Scatter (MSIS) series (Hedin, 1987, 1991), which is based upon data from radar and onboard science instruments, with the newest iteration being NRLMSISE-00 developed by the Naval Research Laboratory (NRL) in 2000 (Picone et al., 2002). Most of these models use the $F_{10.7}$ and K_p indices as inputs, where the former is a measure of EUV irradiance responsible for atmospheric heating and the latter the energy associated with geomagnetic activity. In general, these models do fairly well under stable conditions and low solar activity, but tend to possess a standard deviation of roughly 10–20% (Pardini and Anselmo, 2001; Lean et al., 2002; Vallado and Finkleman, 2014) during more turbulent times. Also, model assumptions and simplifications, which are always inherent, do not capture the full dynamics present in such a complex system.

Another approach to the determination of atmospheric density lies in high quality space-based sensors that either perform measurements or negates the effects of the atmospheric drag. The CHAMP and GRACE satellites carried high-quality accelerometers (Bruinsma et al., 2003; Sutton et al., 2007; Tapley et al., 2007) to estimate perturbations in space. New concepts such as drag free satellites details the use of a suspended proof mass to measure accelerations to high accuracies (DeBra, 1997). Because of these high precision sensors, non-conservative forces can be measured such that gravitational forces do not contaminate the result. However, due to expensive instrumentation and the specific nature of these experiments, the measurements are infrequent and sparse, which results in an incomplete view of the temporal or spatial resolution of Earth's atmosphere.

The last method of determining atmospheric density is to utilize satellite orbits and their decay. High quality position data utilizing laser ranging and GPS has allowed for estimation methods to better model the atmospheric density (McLaughlin et al., 2011; Kuang et al., 2014). It has also been shown that reliable predictions can be inferred from two line element (TLE) datasets of tracked space objects maintained by Space-Track (Picone et al., 2005; Doornbos et al., 2008; Sang et al., 2013). Because of the long history kept in such records and the abundance of measurements themselves, judicious choices of particular satellites with non-varying ballistic coefficients can give a general picture of the atmospheric density over time (Emmert, 2009; Saunders et al., 2011). The High Accuracy Satellite Density Model (HASDM) (Bowman, 2002; Storz et al., 2005) processes Space Surveillance Network (SSN) observations in near real time from a number of calibration satellites in a weighted least squares differential correction method that solves for global density corrections and a state vector for each satellite. As with onboard sensors, one must filter measurements such that there is a successful separation of the drag term from other perturbing forces (e.g. higher order gravity terms, solar radiation pressure and 3rd body effects). The drawback lies in the fact that we require a set of calibration satellites that may be spread quite wide over a large region of space. Constellation launches to remedy this problem are also prohibitively expensive. The temporal resolution of TLE derived density is also limited by the length of the fit span, and although this can be reduced down to an orbit, high quality measurements are necessary in such a case (typically the fit span is around 3 days).

This paper addresses mean atmospheric density estimation from the measurements of multiple satellites within a constellation. Due to the recent advances of CubeSats and increased launch opportunities, the cost of sending these small satellites into LEO have decreased drastically. As a result, we are beginning to see the emergence of LEO constellations, which presents us with a unique opportunity to measure neutral atmospheric density en masse through similar satellites. The loss of CubeSats within this region is almost a non-issue, as replacement from the International Space Station (ISS) or other forms of delivery are frequent and cheap enough to remedy the problem (Toorian et al., 2008).

The focus of this paper is the use of order statistics on TLE measurements (which are derived from ground ranging measurements) to provide a probability density distribution of relative ballistic coefficients, and in turn to deduce the atmospheric density. The application particularly is focused upon estimating mean densities over at least an orbit, where all the satellites are at equivalent altitudes. We have chosen to work with TLEs due to their abundance and overall availability. We are then able to arrive at error statistics from a stochastic viewpoint of the problem. There are two parameters needed for the solution: first, we must have a good estimate of the minimum ballistic coefficient achievable (either from data or physics models), and second, we must have an estimate of the standard deviation of the attitude deviation from its optimum operation (which is assumed to be a flat plate). With these two pieces of information, we can estimate the statistics of the ballistic coefficient.

The paper is organized as follows: Section 2 will describe the data and conditions relevant to the methodology. Section 3 will describe the procedure to estimate the ballistic coefficient, split into subsections: 3.1 describes perturbational methods that feed the data into the prediction procedure, 3.2 describes the ballistic coefficient and density estimation using order statistics and 3.3 outlines the estimation of the minimum ballistic coefficient. Section 4 presents the results of this analysis on 10 satellites in LEO within a specific orbit plane at an altitude of 400 km. Finally conclusions and future work prospects are outlined in Section 5.