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A critical assessment of satellite drag and atmospheric density modeling ☆

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ABSTRACT

This paper examines atmospheric drag models and data usage involved with propagating near-Earth satellites. Many studies, and even some International standards try to promote one model over another, rather than identifying the behavior of the numerous parameters necessary to select the best model for a particular mission and application. We briefly summarize existing information, and quantify sources of uncertainty in satellite propagation resulting from several atmospheric models, or from the treatment of input data indices. The goal is for researchers to understand the relative impact of using different models and data indices so they can properly assess which model and data input to use.

1. Introduction

Significant research has taken place to determine the proper modeling for atmospheric density. The literature contains information in several different disciplines, ranging from basic physics, aerodynamic gas/surface dynamic interactions, orbit determination approaches, to complex models of density, and corrections to existing atmospheric models. Much of the basic research took place almost a half century ago. Jacchia [8], … began a series of atmospheric models that are still in use today. Gaposchkin and Coster [5] evaluated various atmospheric models and found that none solved all the problems of the day. Today, we are in a similar situation, but with significantly more models and data to choose from. Nonetheless, the orbit estimation community often overlooks the assumptions upon which atmospheric models were developed, and vice versa.

Atmospheric models generally use parameters based on observables that are considered indicators of atmospheric density, which are often difficult to measure directly (a_p or K_p, and $F_{10.7}$). Researchers often fix one parameter, such as the drag coefficient, and add others to the state vector to be estimated. In some cases, such as spherical objects, this is appropriate. But for more complex shapes this simply moves the uncertainty to another parameter that might not have any real physical connection to the observables. Occasionally, researchers neglect to recognize that the drag coefficients they estimate depend on the model and assumptions they invoke to make the estimates. This leads to physically unrealistic outcomes.

This paper seeks to clarify the sources of uncertainty in the drag problem, both from the literature, and also from experiments we conducted using various atmospheric

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models, and by treating the input data differently. Much of the work is inherently related to orbit determination and we use the Kalman filter in Analytical Graphic Inc's Orbit Determination Toolkit (ODTK). This program is used in many operational and high precision applications because it is trusted as a robust, flexible, and highly accurate processing platform. Not *all* atmospheric models are tested, nor would it be practical to present data from all the models that exist today. We select from ODTK's available models to expose the characteristics one will find when evaluating models for a particular application.

An important overall consideration is stated. We use propagation comparisons to estimate the effect of various configurations throughout the paper. This is insufficient to accurately measuring what an actual satellite would experience over time, as well as the intricate coupling of all forces, but we are simply trying to demonstrate that several common practices may actually insert significant uncertainty into the solution. The prediction interval is also an important consideration. A 4 to 8-day prediction interval shows the dominant effects. Longer spans risk unnecessarily large errors, and shorter spans may not show the overall effect of input choices and operations. Thus, our approach throughout the paper is to isolate (as much as possible) all other factors and variables, and examine only one item at a time to try and obtain its' contribution to the overall accuracy and operation of using atmospheric drag for satellite calculations.

There are five major areas that we examine (see Fig. 1). This is our approach to organizing and examining the coupled issues of atmospheric density and its effect on satellite motion. In some cases we are able to develop metrics to indicate the effect of one parameter on the overall accuracy. We examine the predominant approaches to predicting atmospheric drag forces. We discuss physical inconsistencies in determining and employing approximations to thermospheric density, and drag coefficients. This should be considered a framework to guide the researcher to an internally consistent approach for calculating atmospheric drag effects on a satellite.

1.1. Basic introduction

There are two fundamental operations that are involved in atmospheric drag: the determination of atmospheric density, and the interaction of the satellite surface with the atmosphere. Much of the recent literature deals with the former, but the latter is an equally important component to the overall effect of atmospheric density on satellite orbits. We examine the case where we have tracking data for satellite objects, determine the ballistic coefficient from the observations, and then use it for predictions.

Ref. [27], Sec 8.6.2 provides the basic fundamentals related to atmospheric drag so we will not repeat all that information here. The widely accepted equation for the acceleration imparted on the satellite from atmospheric drag is

$$\vec{a}_{drag} = -\frac{1}{2}\rho\frac{c_D A}{m} v_{rel}^2 \frac{\vec{v}_{rel}}{|\vec{v}_{rel}|} \qquad (1)$$

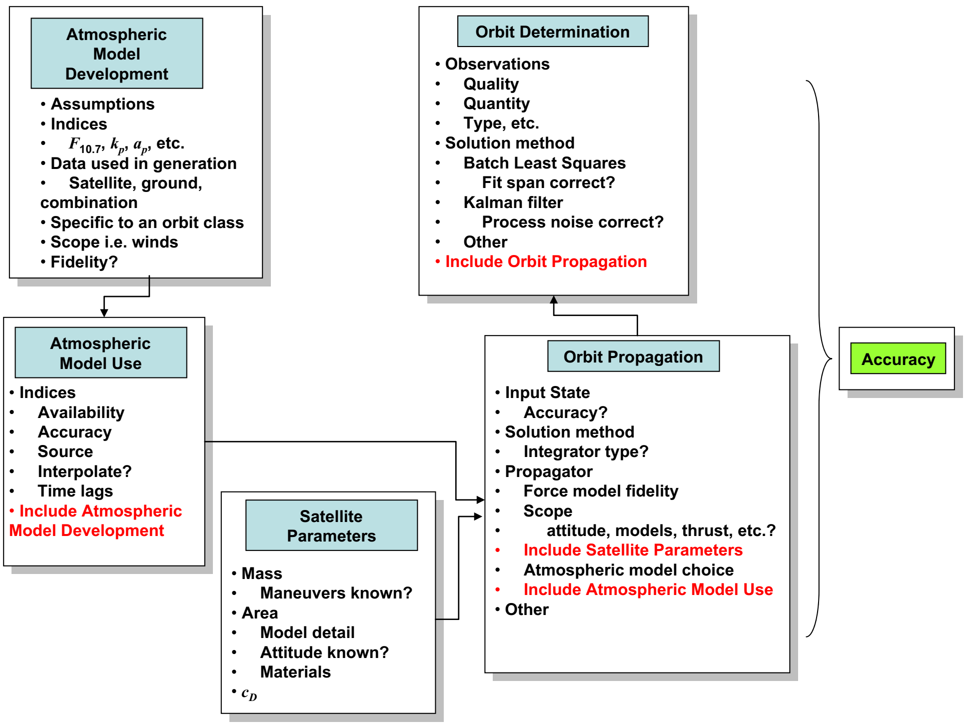

Fig. 1. Variables in the determination of atmospheric drag. Several disciplines are required to properly model atmospheric drag. The relationships show the broad areas we will explore. Note that each of these areas have error bars, some of which are significant. None of them are without error, and many are inter-related.