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Advances in atmospheric drag force modeling for satellite orbit prediction and density estimation

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Atmospheric drag is the largest nongravitational perturbing force acting on low altitude low Earth orbit (LEO) satellites and debris, and the modeling and estimation of drag effects is a limiting problem in the prediction of their orbits over time. The primary sources of uncertainties in drag modeling are introduced due to the atmospheric density and the drag-coefficient. On top of the stochastic variations in atmospheric density, which drive the magnitude of the drag force, there are systematic variations in the drag coefficient due to satellite specific factors and atmospheric conditions. These include satellite attitude shifts, variations in ambient atmospheric parameters such as temperature, molecular composition, and the satellite wall temperature. Thus, even with increasing accuracy of semi-empirical models for the atmospheric density, there remain model uncertainties and time variations in the effective coefficient of drag that affect the satellite's motion, which are not captured using the standard constant drag coefficient model. Though physics-based models of the drag-coefficient can be used to calculate the time-variations in the drag-coefficient, a gap in knowledge of input parameters across orbital regimes and space weather conditions limits their use in operational orbit determination.

This work develops new estimation-based methods to capture the time variations in the drag-coefficient due to attitude changes and orbital motion using Fourier-series expansions. Before implementing these high-fidelity models of drag, a thorough analysis of aliasing effects in estimates of nongravitational force coefficients due to arbitrary truncation of geopotential models is carried out. This allows an informed choice of geopotential degree and order during orbit determination. Improvement in the orbit determination and prediction of simulated and real satellites is demonstrated with the proposed Fourier models. A framework to invert physical parameters from the Fourier coefficient estimates is developed to provide better constraints on physics-based models of the drag-coefficient.

Atmospheric densities derived from satellite tracking data are used in calibration of atmospheric models that are in turn used for orbit determination as well as scientific studies of the Earth's atmosphere. But the derived densities are subject to biases in the assumed drag-coefficient. An important goal of this work is to break out of this circular problem and provide a way to estimate atmospheric densities unbiased by the drag-coefficient. Leveraging the physics of the problem and the Fourier coefficient models, a method to estimate accurate local atmospheric densities at a sub-orbital cadence is developed and reduction in density biases is shown using simulated and real tracking data. Lastly, the new drag-coefficient models are applied to analytical theories of orbital motion in an atmosphere.