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Computational acceleration of orbital neutral sensor ionizer simulation through phenomena separation

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ABSTRACT

Simulation of orbital phenomena is often difficult because of the non-continuum nature of the flow, which forces the use of particle methods, and the disparate time scales, which make long run times necessary. In this work, the computational work load has been reduced by taking advantage of the low number of collisions between different species. This allows each population of particles to be brought into convergence separately using a time step size optimized for its particular motion. The converged populations are then brought together to simulate low probability phenomena, such as ionization or excitation, on much longer time scales. The result of this technique has the effect of reducing run times by a factor of 10^3–10^4. The technique was applied to the simulation of a low earth orbit neutral species sensor with an ionizing element. Comparison with laboratory experiments of ion impacts generated by electron flux shows very good agreement.

1. Introduction

The measurement of neutral species levels in the ionosphere has gained considerable importance due the effects of orbital ionospheric satellite drag [1–4]. Variation in orbital drag can change satellite trajectories and result in difficulties with ground-to-orbit communication. In addition, satellite motion and thruster firings can change the local orbital plasma environment leading to contamination and alteration of fields and the energies of particles surrounding the spacecraft [5–8]. Measurement of the neutral component of the ionosphere is usually carried out with some type of mass spectrometer. These instruments will typically first ionize the incoming flow and then measure the current to characterize the flux. Once the particles are ionized, electric fields can then be used to extract data about the particle energy, composition, or velocity distribution function [9]. In an effort to improve the design of an ionizer element for a neutral particle sensor, numerical simulation can be used to optimize the performance of the instrument. Simulation of these types of flow fields can be very difficult due to the non-Maxwellian nature of the velocity distribution functions, the non-continuum nature of the fluid, and the small ionization fractions involved. All of these problems lead to large computational workloads and long computational times. The present work details the strategies and techniques utilized in the acceleration of the numerical simulation of an ionizing element used in an orbital neutral particle sensor. The purpose of the study is to characterize the amount of current which can be expected from an ionizing element used by such a sensor.

Computation of neutral particle flows in orbit is difficult due to the non-continuum nature of the gas. A parameter often used to determine the expected level of continuum behavior is the Knudsen number, given by,

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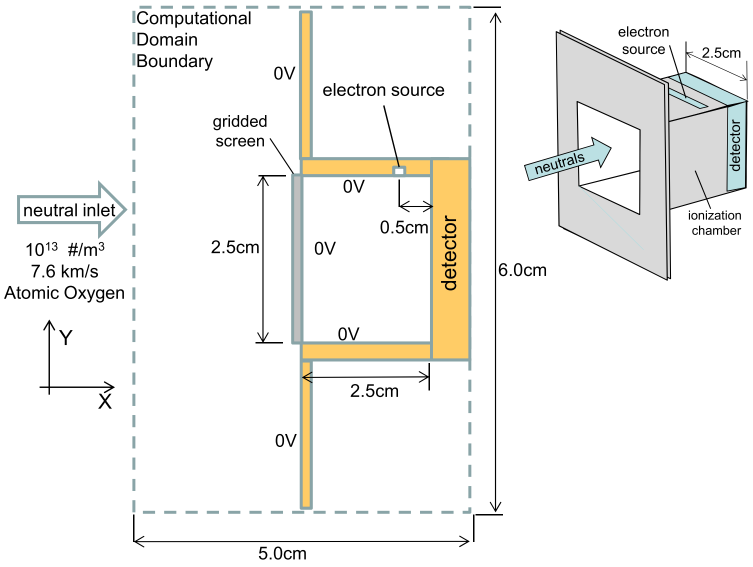

Fig. 1. Computational geometry.

$$Kn = \frac{\lambda}{L} \tag{1}$$

where λ is the mean free path and L is the length scale of the flow. In low earth orbit, the mean free path is measured in thousands of meters [10]. For length scales comparable to a satellite, the Knudsen number, therefore, is greater than 10^3 and the flow is in a free-molecular regime. Therefore, it can not be treated with continuum (fluid) methods. For this reason, particle methods are typically employed in simulations of orbital neutral flows. In the present work, a Direct-Simulation-Monte Carlo [11] (DSMC) technique is utilized to model particle collisions and a Particle-In-Cell [12] (PIC) technique is used to model the effects of electric and magnetic fields.

The computations will attempt to simulate the ionization process in an orbital neutral particle sensor. A schematic of the three-dimensional computational geometry is shown in Fig. 1.

The neutrals enter the computational domain on the left side. The density and velocity are set to be representative of flux of particles on the ram side of a satellite which is in an orbit with a 600 km altitude. A portion of the neutrals will travel through a gridded grounding screen. For the present simulations, the screen is 100% transparent and serves only as a boundary condition for the electric potential. The screen and the walls of the ionization chamber are grounded to the spacecraft chassis. The voltage at the detector can be offset from ground as will be detailed below. Once the neutrals enter into the ionization chamber, they are bombarded by a beam of electrons from a source located on the top of the ionization chamber. The energy of the electrons is set to 100 eV to match the peak of the ionization cross section for atomic oxygen, the dominant neutral in LEO. The resulting ions are then collected in the detector located at the back of the ionization chamber. The geometry is set to be 2.5 cm in the direction normal to the page. The electron emitter is assumed to span the entire ionization chamber in the direction normal to the page. The purpose of the study is to determine the amount of ions which can be expected to reach the sensor after being ionized by the electron beam.

2. Method

The simulation of the flow field detailed above is straight forward but is computationally very intensive. It requires modeling of four major physical phenomena: 1) the neutral flow and associated collisions, 2) the electron flow, 3) the ionizing collisions, and 4) the motion of the created ions. By inspecting each of these phenomena and dispensing with the components which do not affect the velocity distribution functions in a statistically significant manner, the computational workload (run time) can be reduced by orders of magnitude.

We will first examine the neutral flow and associated collisions. The neutral flow will enter with a non-Maxwellian velocity distribution. For the purposes of this study, the neutral velocity distribution in the X (ram) and the Y and Z (perpendicular) directions will be as shown in Fig. 2. The X velocity distribution represents an orbital velocity flow of 7600 m/s with a temperature of 2000 K while the Y and Z velocity distributions represent a neutral population with a temperature of 1000 K. Each distribution is essentially a 1D drifted Maxwellian, although the Y and Z components have no directed velocity. The different X and Z distributions are chosen to be representative of a neutral flow which may be encountered by a sensor mounted on the ram side of a spacecraft. In the computations, these velocity distribution functions (VDF) are sampled in order to generate the population of neutrals entering the computational domain.