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Simulating radiation pressure forces on space objects

Olli Wilkman (1), Guanglang Xu (2), Jouni Peltoniemi (1), Antti Penttilä (2), Olli Ihalainen (2), Niko Kareinen(1), Sonja Lahtinen (1), Maria Gritsevich (2), Jyri Näränen (1), Hannu Koivula (1) and Karri Muinonen (2,1)
(1) Finnish Geospatial Research Institute FGI, Kirkkonummi, Finland, (2) University of Helsinki, Finland
(olli.wilkman@nls.fi)

Abstract

We have developed a ray-tracer designed for simulating interaction between light and space objects. In the present study, it is used to compute radiation pressure forces on a variety of shape models from nanosatellites to large debris objects such as rocket bodies. These forces arise from sunlight and Earthshine illuminating the surface of an object in space. A further numerical methods is also presented, useful for efficiently computing approximations from pre-computed ray-tracer simulations in varying illumination conditions, such as in a dynamical simulation.

1. Motivation

The radiation pressure of sunlight, as well as radiation reflected and emitted by the Earth, cause significant forces on objects orbiting the Earth [3]. The net force alters orbits, while the torques caused by asymmetries in the objects can affect their rotational states. Modelling the radiation pressure accurately is important when accurate orbit predictions are required, e.g. in GNSS satellite operations [1], tracking space debris [4] or making re-entry predictions for deorbiting objects. The effect of the radiation pressure depends on the size, shape, and reflection properties of the object. The force produced scales with the area/mass ratio of the object, making it mostly insignificant for nanosatellites. However, it is signifiant for "traditional" large satellites and the exact cutoff for small satellites between these extremes is hard to define and depends on the satellite and its orbit.

The solar radiation pressure is comparatively well-defined. The Sun is a practically uniform disk approximately half a degree across. The flux of sunlight varies with solar activity and the annual change in the Earth's distance from the Sun. The main complexity of modeling solar radiation pressure is caused by the Earth's shadow, which can occlude parts or the whole of the Sun's disk, depending on the orbit of the satellite.

The Earth radiation pressure is a few orders of magnitude smaller, but still significant in cases where the orbit is studied in detail. It has two components: the directly reflected sunlight ("short-wave"), and the thermal infrared emission of the Earth ("long-wave"). It is much more complex to model in every way: for most satellites, the Earth covers a large portion of the sky, its visible surface is not uniformly illuminated, and its reflectivity and emissivity vary both across the surface and with time. Here we consider mostly the "short-wave" reflected sunlight.

1.1. Methods

We use a ray-tracer simulation to compute radiation pressure forces on various shapes of space objects. The software is a general-purpose tool for modeling various interactions between light and space objects, and can also produce images of the objects under various illumination conditions, as well as disk-integrated spectrometry and simulations of laser ranging observations. The software is developed in the Julia language and will be available under an open-source license once it reaches a more stable state.

The shape models are composed on simple geometric primitives such as spheres, cones, cylinders and triangles. The spectral reflectance properties of the simulated objects are based on laboratory measurements from existing literature as well as new measurements performed at the Finnish Geospatial Research Institute and the University of Helsinki.

A variety of light sources can be used. The most relevant for space object studies are the simulated Sun and Earthshine, as well as an infinitely distant point light. The Earth reflectivity can be represented either with a HealPix discretization [2], or with a simpler spherical harmonic model.

In a dynamics simulation, running the full ray-tracer simulation to compute the radiation pressure forces at each time step would be very time-consuming. For this purpose, the forces can be pre-computed for a number of directions using the distant point light, which can then be used at each time step to approximate an arbitrary illumination distribution and orientation of the object. This process is aided by a scheme to store and represent data on a sphere, such as spherical wavelets or splines. It provides an efficient approximation to the more accurate ray-tracer computation of the forces on a satellite as the illumination changes during its orbit.

2. Summary and Conclusions

Our ray-tracer software can numerically compute the radiation pressure forces and torques on objects with complex shapes and reflectance properties. We use this tool to study the forces on a range of different objects from nanosatellites to large debris, under various illumination conditions. We also use a precomputed set of forces to produce a model that is more efficient to apply in practical cases such as dynamics simulations.

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