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ScienceDirect

Advances in Space Research xxx (2018) xxx–xxx

ADVANCES IN SPACE RESEARCH (a COSPAR publication)

www.elsevier.com/locate/asr

Fast solar radiation pressure modelling with ray tracing and multiple reflections

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Received 17 December 2017; received in revised form 14 February 2018; accepted 18 February 2018

Abstract

Physics based SRP (Solar Radiation Pressure) models using ray tracing methods are powerful tools when modelling the forces on complex real world space vehicles. Currently high resolution (1 mm) ray tracing with secondary intersections is done on high performance computers at UCL (University College London). This study introduces the BVH (Bounding Volume Hierarchy) into the ray tracing approach for physics based SRP modelling and makes it possible to run high resolution analysis on personal computers. The ray tracer is both general and efficient enough to cope with the complex shape of satellites and multiple reflections (three or more, with no upper limit). In this study, the traditional ray tracing technique is introduced in the first place and then the BVH is integrated into the ray tracing. Four aspects of the ray tracer were tested for investigating the performance including runtime, accuracy, the effects of multiple reflections and the effects of pixel array resolution.Test results in runtime on GPS IIR and Galileo IOV (In Orbit Validation) satellites show that the BVH can make the force model computation 30–50 times faster. The ray tracer has an absolute accuracy of several nanonewtons by comparing the test results for spheres and planes with the analytical computations. The multiple reflection effects are investigated both in the intersection number and acceleration on GPS IIR, Galileo IOV and Sentinel-1 spacecraft. Considering the number of intersections, the 3rd reflection can capture 99.12%, 99.14%, and 91.34% of the total reflections for GPS IIR, Galileo IOV satellite bus and the Sentinel-1 spacecraft respectively. In terms of the multiple reflection effects on the acceleration, the secondary reflection effect for Galileo IOV satellite and Sentinel-1 can reach $0.2\ \mathrm{nm/s^2}$ and $0.4\ \mathrm{nm/s^2}$ respectively. The error percentage in the accelerations magnitude results show that the 3rd reflection should be considered in order to make it less than 0.035%. The pixel array resolution tests show that the dimensions of the components have to be considered when choosing the spacing of the pixel in order not to miss some components of the satellite in ray tracing. This paper presents the first systematic and quantitative study of the secondary and higher order intersection effects. It shows conclusively the effect is non-negligible for certain classes of misson.

Keywords: SRP modelling; Fast ray tracing; Multiple-reflection; GPS IIR; Galileo IOV; Sentinel-1

1. Introduction

SRP (Solar radiation pressure) has effects on all the artificial satellites. It is the largest non-gravitational force for high altitude satellites. Take GNSS (Global Navigation Satellite System) satellites as an example, SRP force will make them drift several hundred meters in one day (Springer et al., 1999; Montenbruck and Gill, 2005; Ziebart et al., 2005). Thus it is very important to accurately model SRP for the sake of orbit quality.

Currently, the strategies for SRP modelling presented in the precise orbit determination community may be broadly divided into two categories. The first category is the

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https://doi.org/10.1016/j.asr.2018.02.019

0273-1177/

Please cite this article in press as: Li, Z., et al. Fast solar radiation pressure modelling with ray tracing and multiple reflections. Adv. Space Res. (2018), https://doi.org/10.1016/j.asr.2018.02.019

empirical approach. Triangular functions like sine and cosine are used in the along track, radial and cross track to absorb the un-modelled non-gravitational forces. This method has been applied to the orbit determination of many missions such as Sentinel-1 (Peter et al., 2017), Jason (Cerri et al., 2010), HY-2A (Gao et al., 2015), GRACE (Gravity Recovery and Climate Experiment) (Kang et al., 2006), GOCE (Gravity field and steady-state Ocean Circulation Explorer) (Casotto et al., 2013) and GNSS satellites (Sibthorpe et al., 2011; Arnold et al., 2015). Although this approach has been widely used by the community, it does have drawbacks. One aspect is that in the estimation of empirical parameters, there is a risk of mixing orbit dynamic parameters with other physical parameters such as earth orientation parameters and geocentre (Meindl et al., 2013). The other aspect is that the parameters in the empirical model have no clear physical meaning which means it is less helpful for understanding what really happened to the satellites in space.

The second category is to develop high-fidelity SRP model that considers the interactions between solar rays and satellite surfaces. This approach is very convenient for analysing the effects of different physical parameters on the orbit. In addition, in the data processing of precise orbit determination, the high-fidelity model can also help to reduce the correlations between estimates which means a tight constraint is introduced on these parameters. In practice, the tight constraint can improve the estimated parameters (Ziebart, 2004; Solano, 2014; Cerri et al., 2010).

However, the complex shape and multiple materials of the satellite surfaces have to be considered in developing the high-fidelity SRP model. One way to deal with this problem is by using the ray tracing technique. For satellites that have dynamic components such as the solar panels of GNSS satellites, the calculation of the dynamic components are separated for the efficiency of ray tracing though this may cause ignoring of shadowing effect from solar panels to the satellite bus. For the satellites that with all the components fixed such as Sentinel-1, the ray tracing can be applied directly.

The ray tracing technique accounts for the interactions between each ray and satellite surfaces. But the number of rays can reach over 2.5×10^7 for satellites with a size of $5 \times 5\,\mathrm{m}^2$ at only one direction of solar flux. Therefore, it is necessary to find a way to make this ray tracer more efficient in computation.

Generally, this problem can be solved from two aspects. One aspect is to reduce the number of rays that needs to be calculated. The other aspect is to speed up the process of finding the intersections between rays and the spacecraft surfaces. Thus two questions will be produced with respect to the above two aspects. (1) How is the spacecraft geometry represented? (2) How to find the intersections as quick as possible? Regarding the first question, the satellite bus is represented by simple geometries that can be described by mathematical equations. The intersections can be calculated in an analytical way with this representation. As for the second question, there exits the first attempt to speed up the modelling computation by using block modelling approach (Sibthorpe, 2006). In this study, the BVH (Bounding Volume Hierarchy) data structure is used in organising the components of the satellite bus. The essence of the BVH is a binary tree (or K-Dimensional Tree) that stores primitives in the scene where each node represents a bounding volume (Lauterbach et al., 2009; Bittner et al., 2015).

This paper firstly introduces the physical basis of SRP and is followed by the general ray tracing approach for SRP modelling. The representation of the satellite bus geometry and the intersection algorithm for each geometry are described along with the implementation of the ray tracer. Secondly, the BVH data structure is applied to the ray tracer to improve the performance. This BVH data structure reorganises the components of the satellite bus and speeds up the process of searching for the possible intersection components. Finally, the performance of the ray tracer is tested in four aspects, including absolute accuracy, runtime, the effects of multiple reflections and the effects of pixel array resolution.

2. The physics of radiation pressure

The physical foundation is the basis for solar radiation pressure modelling. The theory of radiation pressure was revealed by Maxwell as an assertion based on his theory of electromagnetism. The radiation pressure phenomenon was then validated in experiments by Lebedev (1901), Nichols and Hull (1902) and Nichols and Hull (1903). According to Maxwell's theory, an electromagnetic wave carries momentum which can be transferred to a reflecting or absorbing surface hit by the wave. The momentum change will generate a force on the surface. By applying Einstein's special theory of relativity and the theorem of impulse, the force generated by the electromagnetic wave is obtained. For a photon of frequency f, the momentum p is given

$$p = \frac{hf}{c} \tag{1}$$

where h is Planck's constant.

Fig. 1 shows the process of reflection that happened on a plane. Assume there are N_f photons at frequency f in the incident ray going through unit area at unit time dt, $v_f N_f$ photons are reflected. Within the reflected photons, there are $\mu_f v_f N_f$ photons getting specularly reflected and $v_f(1-\mu_f)N_f$ photons getting diffusely reflected. For the diffuse reflection, assume the surface meets the requirement of Lambert assumption which means the intensity of the ray falls off by a factor of $\cos\theta$ away from the normal to the surface. The proportion of diffusely reflected radiation that is emitted normal to surface is $\frac{2}{3}$ (Ziebart, 2004; Fliegel