Earth Radiation Pressure Modeling for BDS IGSO satellite

Zhen LI[1], Marek ZIEBART, Stuart GREY and Santosh BHATTARAI

Abstract. This study shows ERP (Earth Radiation Pressure) is significant for precise orbit determination of BeiDou satellites, systematic error is observable in the orbit products if it is ignored in the orbital dynamics. Through subdividing CERES (Cloud and Earth Radiation Energy System) 1° by 1° earth radiation grid into 6 levels of triangles, a precise and runtime configurable earth radiation model has been obtained. The results reveal that level 4 subdivision can make the relative error of both longwave and shortwave radiation less than 1%. ERP acceleration for BeiDou IGSO satellite(C08) and its effects on orbit have been analyzed through modelling the earth radiation using a box-wing geometry model. The acceleration in radial is about 2-4 times larger than the along track and normal with magnitude $10^{-10} m/s^2$. 30-hour orbit prediction shows the 3D RMS error due to ERP is 0.638 m and its maximum can reach 0.9 m.

Keywords: Earth Radiation Pressure. BDS IGSO. Earth Radiation Model

1 Introduction

The ERP (earth radiation pressure) is one of the radiation forces that acted on spacecraft. The effects to GPS orbit have been identified, it is reported that ERP will make both the orbit and the station position systematic biased [1-3]. However, in the precise orbit determination process, the empirical SRP (solar radiation pressure) parameters and custom accelerations are estimated which is thought to have included all the forces. There are some disadvantages in the current processing methods. On one hand, this kinds of estimations will inevitably make the parameters correlated and as a consequence weak the observation equations. On the other hand, the estimated parameters have no clear physical meanings which makes the orbit analysis difficult. Therefore, it is necessary to deal with this problem from the perspective of physics. There are already some SRP (solar radiation pressure,

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which is the largest among all the non-conservative forces) models which are built using the physical mechanics [4-5], but the researches on the ERP for BDS satellites are rare. The most widely used ERP for GPS is the Knocke Model developed twenty years ago [6]. Even though the modelling methodology of ERP is similar as that of SRP, the characters of ERP accelerations can be different due to the changes of earth radiation and the attitude of the spacecraft. In terms of the different orbit types(GEO/IGSO/MEO) of the BDS constellation, ERP will affect the orbit in different way.

The modelling for ERP basically includes two parts, one is the earth radiation modelling and the other part is satellite geometry. The earth radiation that reaches the satellite will mainly determine the scale factor of ERP acceleration, but it will also affect the directions of ERP accelerations as well due to the unevenly distribution of earth radiation for the orbit. The satellite geometry and optical properties are of great importance in the modelling of radiation pressure forces. The accurate satellite geometry and surface optical properties are even more important than the incoming radiation according to the research for GPS [1]. In this study, the precision and runtime configurable earth radiation model is built based on CERES (Cloud and Earth Radiation Energy System) radiation measurements firstly, then the interaction of photons and the surface of satellite is considered based on box-wing satellite model. The analysis on the characters of ERP acceleration on IGSO orbit is done under the yaw steering attitude mode. In order to obtain the impacts of ERP to the orbit, 30-hour orbit prediction is done.

2 Earth Radiation Modelling

NASA's CERES project uses space crafts which carry radiometers to measure the irradiance that reaches the TOA (top of atmosphere) for the energy balance purpose [7-9]. Apparently, the data can also be used for other researches relate the earth radiation. According to the classification of spectral range for CERES detectors, the wavelength ranges of shortwave is 0.3 to 5 microns, the wavelength ranges of longwave is 8 to 12 micros. The total detect range is from 0.3 to 100 microns [8]. The data sheet is provided in the format of netcdf which is widely used in the research of atmosphere. For the earth radiation data sheet, CERES can provide them monthly in the space resolution of 1deg by 1deg. Figure 1.1 and Figure 1.2 show the shortwave flux and longwave flux of the CERES grid in June separately. The average radiation flux of longwave is about 250 w/m^2 while the average radiation flux of shortwave is about 100 w/m^2. The distribution of the radiation flux changes with time.

However, given the position of the spacecraft in ECEF (earth fixed earth centered), the searching of visible area for the satellite can be very slow and inefficient with this 1deg by 1deg grid. Therefore, to make this process running faster is one of the motivation of modelling the earth radiation. The other motivation is to obtain a balance between accuracy and runtime, because for higher orbit spacecraft, the earth radiation can be smaller, that means the modelling of earth radiation need not to be so detailed, but for LEO (low earth orbit) satellite, the effect of earth radiation can be larger, it is necessary to use a detailed earth radiation model. In this study, the accuracy and runtime configurable earth radiation model is built to suit all the situations.

Generally, the modelling method is just reorganizing the CERES raw grid data and put the radiation value into different level of triangular grids which makes it easy to control the area of each triangle. For each of the triangle, the radiation flux should be scale according to the position of the spacecraft. Then the ERP acceleration can be calculated based on each of the triangular radiation flux.

2.1 Subdivision of TOA into triangles

Basically, the CERES radiation data is collected at the top of atmosphere. The definition of TOA is a surface approximately 30 km above the earth surface [8]. It is described with an ellipsoid equation with semi-major axis a = 6408137 meter and polar radius b = 6386651.7 meter. For simplification, a sphere is used to approximate the ellipsoid TOA with radius $r = \sqrt{ab}$.

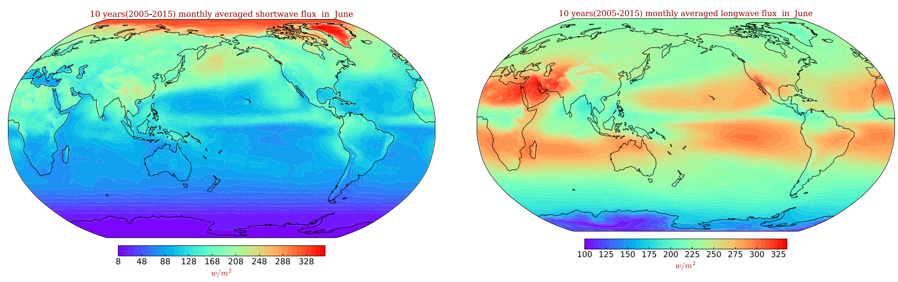

Fig. 1.1 The 10 years (2005-2015) monthly averaged shortwave(left) and longwave(right) radiation flux in June

Starting from a regular octahedron, with two vertices as the north and south pole differently, the other four vertices evenly distributed on the equatorial plane. The situation is showed at level 0 in Figure 1.2. The middle points on three edges of one triangle is chosen to generate the next level of triangle. The total number of triangles is 8×4^n where n is the number of level counting form 0. Because the raw grid is in 1deg by 1deg and there is no need to make the current triangular grid smaller than the original one, thus the maximum level can be 6 where the average area of triangle is 15565.932 km^2. the triangles can be evenly distributed at TOA. Actually, the ratio between maximum area and minimum area is 2.1 for level 6 where the minimum triangle is on the north and south pole and the maximum triangle appears at equator.

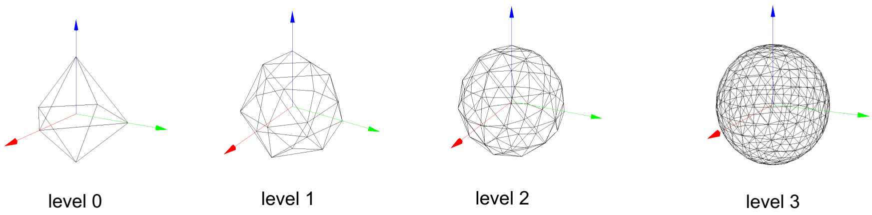

Fig. 1.2 The subdivision process of the triangular grids

2.2 Visibility test and scaling of radiation flux

The visibility test for a given spacecraft is done based on the elevation of the spacecraft for the certain point on TOA. If the elevation is larger than 0 it is visible for the satellite. Appling this to every triangle, the visible area of the spacecraft can be obtained. Figure 1.3 shows the visibility area for one IGSO (Inclined Geosynchronous Orbit) satellite. Once the visible area is determined, the radiation flux for every triangle is obtained including both flux value and flux direction. The propagation of radiation satisfies the the inverse square law. Because the TOA surface is hackly and is considered a lambertian radiator, so the earth radiation flux is assumed to be diffuse reflection (both shortwave and longwave radiation). The transfer of radiation in a vacuum environment from one surface to another can be described succinctly by the differential form of the fundamental equation of radiative transfer [10]. It is

$$d\emptyset = L\frac{dA_1 cos\theta_1 dA_2 cos\theta_2}{\rho^2} \tag{1.1}$$

where L is the radiance from either surface to the other, A is an area, θ is the angle between a surface normal and the line of sight between surfaces, ρ is the line of sight distance. $d\phi$ is the exitance radiation. For this earth radiation case, this formula becomes:

$$\emptyset = A_0 L \int_0^{2\pi} \int_0^{\pi/2} sin\theta cos\theta d\theta d\varphi \tag{1.2}$$

here, ϕ is the exitance radiation energy, θ and φ are the angles used to locate the difference area on semi-sphere, A_0 is the area of the certain triangle. Therefore, the exitance radiation flux M is:

$$M = \frac{\phi}{A_0} = \pi L \tag{1.3}$$

This formula means for lambertian radiator; the radiance is the radiant exitance divided by π. Considering the inverse square law, for every triangle the radiation which reaches the satellite can be:

$$P_r = \frac{P_{tri} A_{tri} cos\theta}{\pi r^2} \tag{1.4}$$

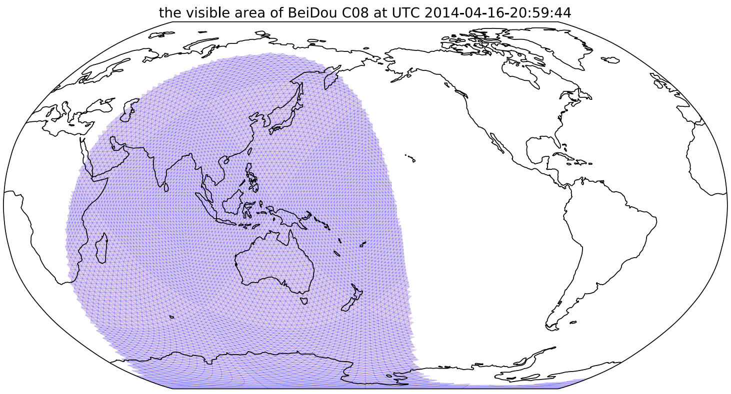

Fig. 1.3 The visible area of BDS C08 at UTC 2014-04-16-20:59:44

2.3 Earth Radiation Analysis

In order to test the effects of different level triangular subdivision to the earth radiation, one BeiDou IGSO satellite is chosen to show the radiation which reaches the satellite. The testing time is from 2014-04-16:21:00:00 to 2014-04-18:03:00:00. Figure 1.4 and Figure 1.5 show the changes of longwave flux and shortwave flux that reaches the satellite separately. The results show that level 4 is sufficient for the calculation of earth radiation. The relative error comparing with CERES raw grid is revealed in Table1.1, level 4 subdivision can ensure the relative error less than 1% for both longwave and shortwave flux.

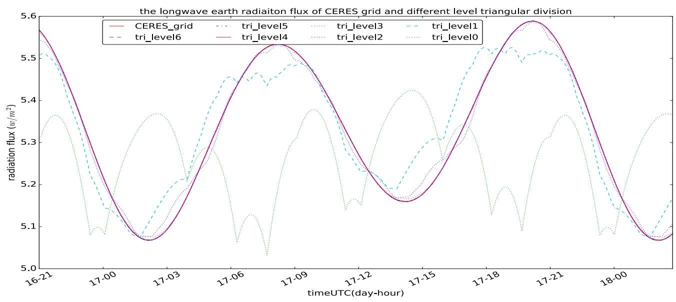

Fig. 1.4 The evolution of longwave flux of C08 for different levels

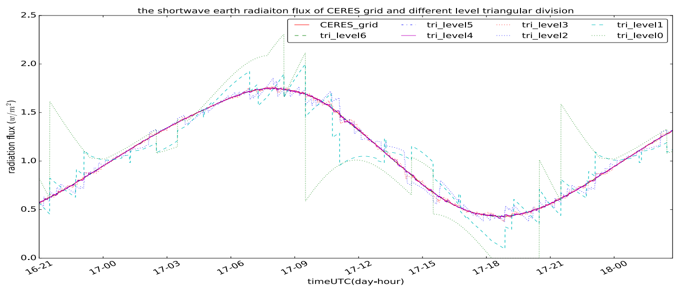

Fig. 1.5 The evolution of shortwave flux of C08 for different levels

Table1.1 The RMS error percentage of flux magnitude with different level subdivision for BeiDou C08(unit: w/m^2)

level	rms(shortwave)	rms(longwave)	rel.error(shortwave)	rel. error(longwave)	runtime(ms)
Level0	0.3676	0.2218	34.598%	4.167%	0.016
level1	0.1532	0.0574	14.420%	1.078%	0.041
level2	0.0553	0.0145	5.203%	0.273%	0.128
level3	0.0175	0.0031	1.655%	0.059%	0.556
level4	0.0061	0.0006	0.576%	0.0126%	1.35
level5	0.0023	0.0002	0.214%	0.003%	4.83
level6	0.0008	3.957E-5	0.082%	0.001%	14.79

In order to show the CERES earth radiation flux can capture more details, the average longwave flux value 239.6 w/m^2 is chosen to make this comparison. Figure 1.8 shows that for the constant longwave flux situation, it reaches maximum at perigee and the minimum at apogee. However, for the level 4 triangular subdivision situation, it does reach maximum at perigee but the minimum does not appear at apogee, this is due to the unevenly distribution of the earth radiation.

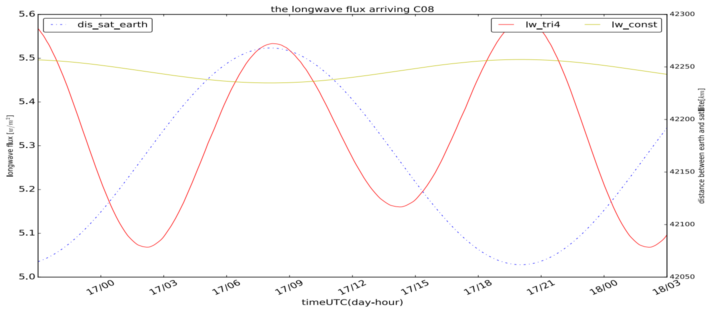

Fig. 1.6 The difference between constant earth flux and flux from level 4 triangular division

3 Satellite Geometry and Radiation Acceleration

Once the earth radiation is determined, the acceleration can be calculated according to the physical process of interaction between photons and surfaces. Due to lack of detailed information about the spacecraft, a box-wing geometry model is used to do the calculation. Table1.2 shows the satellite geometry and optical property used in the calculation [11].

Table1.2 the geometry and optical property of BeiDou IGSO/MEO satellite(mass=1386.6kg)

component	area(m^2)	reflectivity	specular reflectivity
X	3.784	0.65	0
Y	4.400	0.86	0
Z	3.440	0.65	0
solar panel	11.352*2	0.28	0.85

3.1 ERP acceleration analysis

The ERP force is shown in orbital RTN (Radial, Tangent, Normal) coordinate system. The figure 1.7 shows that the ERP force is not only at the radial direction, apparently radial component is the largest. The tangent and normal direction component is because the yaw steering attitude of the solar panel. The radial component gets its minimum value when the solar panel normal is perpendicular to the earth radiation, at this time the earth radiation will illuminate from backside to foresight of the solar panel or in contrast. For this IGSO satellite, the apogee is just about 200 km larger than the perigee, thus earth radiation is quite similar. However, because of the attitude changing, the maximum acceleration appears near orbital apogee which is a different conclusion against the common sense.

The magnitude of the ERP force is at 3×10^{-7} Newton, if the mass of the satellite is 1000 kg, then the acceleration can be $3\times10^{-10} m/s^2$. The magnitude of acceleration in radial direction is 3 times greater than the tangent and normal direction. From this case, it is revealed that the attitude of the spacecraft is very important in modelling the non-conservative forces. What have shown is just the ERP acceleration for box-wing satellite model, if it were the real satellite, it could be more complex and the characters of ERP is worth to research for more accurate orbital dynamic modelling.

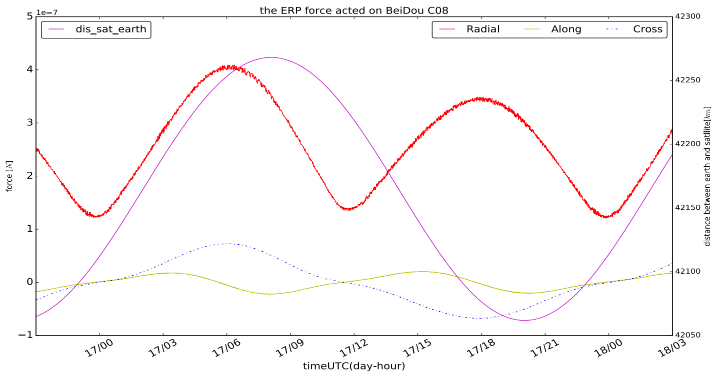

Fig. 1.7 The interaction between incident ray and one plane

3.2 Orbit prediction analysis

The orbit prediction for one IGSO satellite(C08) shows that the effects of ERP is not negligible. The initial position and velocity for this prediction is chosen from the precise ephemeris products from IGS MGEX. The force models include EGM2008(20 degree) gravity model, third body gravity (Sun, Moon, Jupiter), general relativity, solid earth tide, polar tide, solar radiation pressure (this model is derived using ray-tracing approach developed at UCL) and earth radiation pressure. Figure 1.8 shows the 30 hours orbit prediction results with and without ERP acceleration. ERP acceleration has less effects at the cross direction, but it affects the along track the most. Similar results have been shown in Solano's work at 2009 for GPS satellite [1]. In these three directions, the orbit error can reach to

0.2,0.0 and 1.0 meters separately. The 3D RMS of orbital error due to ERP is 0.638 meter while the maximum value can reach 0.9 meters. The reason for this interesting result is that the radial acceleration will make the velocity smaller (which is basically in the along track), that's why the along track orbit error is always negative.

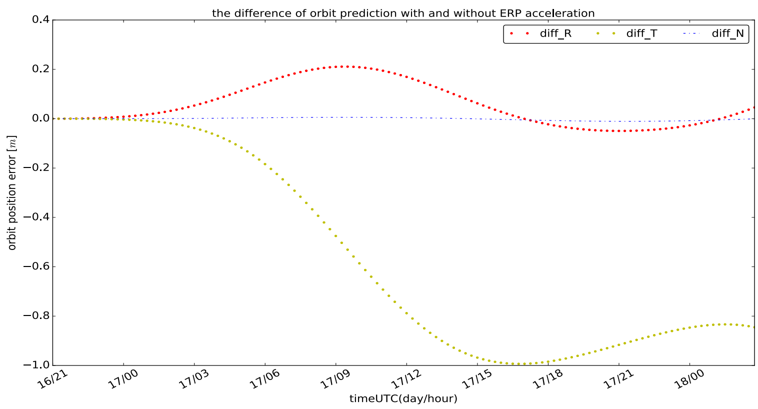

Fig. 1.8 The different of orbit prediction with/without ERP

4 Summary and Conclusions

One both precision and runtime configurable earth radiation model has been established. Based on this radiation model, the ERP force which acted on BeiDou IGSO satellite is calculated. The characters of ERP force is detailed analyzed. According to the orbit prediction results, the along track direction is affected the most, thus it is very important to make the along track ERP acceleration accurate. The along track acceleration is due to the two reasons, one is the earth radiation does not only illuminate the +Z face of the satellite, it will also shine the +X and +Y partly. The other reason is the yaw steering attitude change of the solar panel, it would make even the radial earth radiation has an along track component. The orbit prediction result shows that the ERP acceleration affects the along track orbit the most. The orbit error can even reach about 1 meter after one day's prediction.

5 References

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