Impact Analysis of Solar Irradiance Change on Precision Orbit Determination of Navigation Satellites

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(Received 17 April 2019; revised 20 December 2019; accepted 22 December 2019)

Abstract: Solar radiation pressure is the main driving force and error source for precision orbit determination of navigation satellites. It is proportional to the solar irradiance, which is the "sun constant". In regular calculation, the "solar constant" is regard as a constant. However, due to the existence of sunspots, flares, etc., the solar constant is not fixed, the change in the year is about 1%. To investigate the variation of solar irradiance, we use interpolation and average segment modeling of total solar irradiance data of SORCE, establishing variance solar radiation pressure (VARSRP) model and average solar radiation pressure (AVESRP) model based on the built solar pressure model (SRPM) (constant model). According to observation data of global positioning system (GPS) and Beidou system (BDS) in 2015 and comparing the solar pressure acceleration of VARSRP, AVESRP and SRPM, the magnitude of change can reach 10^{-10} m/s^2. In addition, according to the satellite precise orbit determination, for GPS satellites, the results of VARSRP and AVESRP are slightly smaller than those of the SRPM model, and the improvement is between 0.1 to 0.5 mm. For geosynchronous orbit (GEO) satellites of BDS, The AVESRP and VARSRP have an improvement of 3.5 mm and 4.0 mm, respectively, based on overlapping arc, and SLR check results show the AVESRP model and the VARSRP model is improved by 2.3 mm and 3.5 mm, respectively. Moreover, the change of inclined geosynchronous orbit (IGSO) satellites and medium earth orbit (MEO) satellites is relatively small, and the improvement is smaller than 0.5 mm.

Key words: solar pressure acceleration; total solar irradiance; precise orbit determination; global positioning system (GPS); Beidou system (BDS)

CLC number: P228 **Document code:** A **Article ID:** 1005-1120(2019)06-0889-13

0 Introduction

Solar radiation pressure is an important research topic in the precision orbit determination of navigation satellites. At present, the widely used solar radiation pressure models include three types in the precision orbit determination of navigation satellites: Analytical solar radiation pressure (SRP) models, semi-empirical and semi-analytical SRP models, and empirical SRP models. The analytical models and the semi-analytical and semi-empirical models need to use the solar constant while calculating the solar radiation force. The solar constant is the receiving solar radiation flux density which is perpendicular to the solar ray surface in the upper limit of the Earth's atmosphere, with an unit of W/m^2. In general, the solar constant is treated as a constant among the SRP models, and its value varies with the times. At present, most scientists choose the value of 1 368 W/m^2. In fact, however, the solar constant is not a constant. In 1983, Climate Change[1] published the Nimbus-7 satellite measure-

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How to cite this article: ZHANG Yan, WANG Xiaoya, XI Kewei, et al. Impact Analysis of Solar Irradiance Change on Precision Orbit Determination of Navigation Satellites[J]. Transactions of Nanjing University of Aeronautics and Astronautics, 2019,36(6):889-901.
http://dx.doi.org/10.16356/j.1005-1120.2019.06.002

ments: The solar constant is changing. The valley values of most solar constant changes are corresponding to the peak of sunspots day by day. This is because the temperature of sunspots is lower than that of the surface of the photosphere, and solar radiation will decrease naturally with the increase of sunspots. This view is at variance with the most cognitions of scientists. It is generally believed that the activity of sunspots will increase and the solar radiation will increase. Foukal et al.[2] solved this problem. They thought that sunspots reducing solar radiation is a short-term behavior. When sunspots increase, the flares also increase. As a result of the increase of the flares, the solar radiation will increase, and the solar radiation increased by the flares is larger than the decrease due to the sunspots. So solar radiation is generally increased. Therefore, the solar constant shows a trend of synchronization with the sunspot in an 11-year cycle, so more and more scientists and research institutions have chosen solar irradiance or total solar irradiance (TSI), which is a more rigorous statement, instead of the term of solar constant.

In this paper, we use the measured solar irradiance data obtained by space observation to analyze the variation characteristics of solar irradiance. For global positioning system (GPS) and Beidou sysem (BDS) navigation satellites, we analyze the effects of solar irradiance change on solar pressure acceleration and its orbit determination accuracy. This provides a basis for considering the effect of global navigation satellite system (GNSS) high precision orbit determination.

1 Solar Irradiance and SRP

1.1 Current status of solar irradiance research

The solar irradiance is the receiving solar radiation flux density, which is perpendicular to the solar ray surface in the upper limit of the Earth's atmosphere at the average distance (D=1 AU=1.496×10^8 km), and the unit is W/m^2. Solar irradiance is a relatively stable value: It is based on changes of the activity of sunspots, including all forms of solar radiation. It is constrained by solar activities and it has various temporal scale characteristics. In early days, the measurement of solar irradiance was based on the known mass of water placed in the sun for a period of time. The temperature rising process was measured with a thermometer, and the sunlight intensity could be calculated because the specific heat capacity of the water was known[3]. Claude Pouillet and John Herschel designed different devices according to this principle and measured the value which was about 680 W/m^2[3]. Abbot[4] measured the solar irradiance based on ground-based measurements at a high-altitude observation for many years. The measurement result was 1 302—1 465 W/m^2.

The Nimbus-7 meteorological satellite was successfully launched and it began to accurately measure the solar irradiance, thus the misunderstanding of the "solar constant" was changed. In 2003, the University of Colorado Boulder's Laboratory for Atmospheric and Space Physics used the total irradiance monitor (TIM)[5] radiometer to measure the solar irradiance value every day or every 6 h, as shown in Fig.1. It can be seen that there is a solar activity cycle of about 11 years. Table 1 gives the TSI mean values for satellite measurements from different ages[6]. The mean value of solar and heliospheric observatory (SOHO) is 1 365 W/m^2, and that of TIM is 1 361 W/m^2. According to Kopp et al.[7], this is because the instruments used to measure solar irradiance on satellites are not different from those used on the ground in the past. In addition, most of the previous instruments were calibrated with world radiometric reference (WRR) before

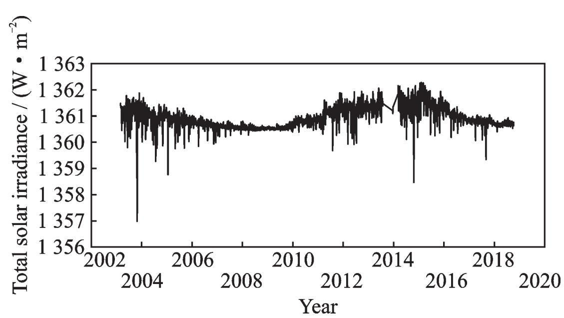

Fig.1 Solar irradiance time series measured by TIM/SORCE during 25 Feb., 2003 to 5 Dec., 2018

Table 1 The mean TSI of satellite measurements in different ages

Measurement/Satellite	Year	TSI/($W \cdot m^{-2}$)	Author
ERB/Nimbus-7	1978—1993	1 371	Hickey et al.[1] Hickey et al.[1]
ACRIM-I/SMN	1980—1989	1 367	Willson et al.[8]
ERBE/ERBS	1984—2003	1 365	Lee et al.[9]
ERBE/NOAA9	1985—1989	1 364	BarkstRom et al.[10-11]
ERBE/NOAA10	1986—1987	1 364	BarkstRom et al.[10-11]
ACRIM-II/UARS	1991—2001	1 365	Willson[12]
SOVA 1/EURECA	1992—1993	1 365	Crommelynck et al.[13]
DIARAD/VIRGO on SOHO	1996—Now	1 365	Dewitte et al.[14]
PMO6V/VIRGO on SOHO	1996—Now	1 365	Froehlich et al.[15] Froehlich et al.[16]
ACRIM-III/ACRIMSAT	2000—Now	1 365	Willson & Helizon[17]
TIM/SORCE	2003—2013	1 361	Kopp et al.[7]
PREMOS/PICARD	2010—Now	1 361	Schmutz et al.[18]

launch, and the current instruments are based on the system international (SI). The WRR itself is relatively higher than the SI irradiance standard, which results in low values[6,19].

It can be seen that the values of different solar irradiance instruments are basically the same, the solar irradiance is not constant, but there is a solar activity cycle change, and the variation range is about 0.1%. For the solar irradiance data of SORCE based on the work of the predecessors, the accuracy has been improved by ±0.035%[20].

1.2 Solar irradiance theory derivation

The solar radiation power comes from the gravitational self-polymerization energy of the sun, that is, the gravitational potential energy of the sun[21]

$$\Omega = -0.6 \times GM^2/R \tag{1}$$

where M is the solar mass, G the universal gravitational constant, and R the solar radius. Considering the two-body problem of the sun and the earth, time and space are the basic forms of the existence of moving matter, and the basic properties inherent in the object. Time and space are inseparable from the moving matter, so time factor is introduced in the physical quantity for the two-body problem[22-23]

$$M=M_0 \times \exp(Ht), R=R_0 \times \exp(-Ht) \tag{2}$$

where H is the Hubble coefficient of the sun. After Eq.(2) is substituted to Eq.(1), it is obtained as

$$\Omega=-0.6\times(GM_0^2/R_0)\times\exp(3Ht) \tag{3}$$

The solar radiation power is the differential of Ω versus time t

$$P= \mathrm{d}\Omega/\mathrm{d}t=-1.8\times(GM^2/R)\times H \tag{4}$$

According to the relationship between solar irradiance and solar radiation power

$$\Phi_0=1.8\times(GM^2/4\pi Rr^2)\times H \tag{5}$$

where Φ_0 is the solar irradiance, r the distance between the earth and the sun. We choose 1 AU.

According to astronomy constants, $G=6.674\ 184\times10^{-11}$ $\mathrm{N \cdot m^2/kg^2}$, 1 AU$=1.495\ 978\ 70\times10^{-11}$ m, $H\approx6\times10^{-16}$ s^{-1}, $M=1.988\ 47\times10^{-30}$ kg, $R=6.959\ 97\times10^{11}$ m. And we get $\Phi_0=1\ 456.841$ $\mathrm{W/m^2}$.

Comparing the above results with the measured values of the satellites, we can see that the theoretical calculations are large. This is probably because among the solar radiation calculation, the sun is not a simple point source, but a group of beam arrays, so the theory does not fully reflect the true situation of solar radiation, which means that the theory of solar radiation needs to be developed before it can be consistent with actual observations.

The theory of solar irradiance is also inferred to from radiation propagation theory with regard to solar radiation power. According to Stefan-Boltzmann's law, the relationship between the radiant energy E_T per unit area of the sun and the temperature T is

$$E_T=\sigma T^4 \tag{6}$$

where σ is the Stefan-Boltzmann constant. The total radiant energy E of the sun is

$$E=E_T S \tag{7}$$

where S is the surface area of the sun. When solar radiation is isotropically radiated outward in the sphere space, the solar radiation received in a unit area from the sun with the distance of r is the solar irradiance Φ_0

$$\Phi_0=E/4\pi r^2 \tag{8}$$

Organize the above formulas

$$\Phi_0=\sigma T^4 S/4\pi r^2 \tag{9}$$

where r is the distance between the earth and the sun. We choose 1 AU.

According to astronomy constants, $\sigma=5.67\times 10^{-8}$ W/m²·K⁴, 1 AU=$1.495\,978\,70\times 10^{11}$ m, $T=5\,780$ K, $S=6.087\,35\times 10^{18}$ m². And we get $\Phi_0=1\,369.815$ W/m².

1.3 SRP models

According to the principle of the SRP model, the satellite can be decomposed into a plurality of components having different shapes and sizes. For the solar radiation force of the differential element of the satellite component, it can be expressed as[24]

$$\mathrm{d}F=-\lambda\frac{\Phi_0}{c}\left(\frac{\mathrm{AU}}{r_{\mathrm{ss}}}\right)^2\cos\theta\mathrm{d}A\left\{2\nu\left[\mu\cos\theta+\frac{(1-\mu)}{3}\right]\hat{\boldsymbol{n}}+(1-\mu\nu)\hat{\boldsymbol{p}}\right\} \tag{10}$$

where λ is the eclipse factor of the satellite; Φ_0 the solar irradiance at 1 AU; c the speed of light; r_{ss} the distance from the satellite to the sun; dA the differential area element of the satellite; $\hat{\boldsymbol{n}}$ and $\hat{\boldsymbol{p}}$ are the the normal vector of the element area and the direction vector of the satellite to the sun, respectively; θ is the angle between the normal of the area element and the direction of the satellite to the sun; μ the specular reflection coefficient, and ν the reflectivity. Then the solar radiation pressure acceleration is[24]

$$\boldsymbol{a}_{\mathrm{SRP}}=\int\frac{\mathrm{d}F}{m} \tag{11}$$

ROCK4 and ROCK42 are the first analytical SRP models established by satellite manufacturers Rockwell International and IBM for GPS Block I and Block II/IIA satellites, respectively. Fliegel et al.[25] have made thermal radiation corrections for the ROCK model to establish T10 and T20 models, then Fliegel et al.[26] used the detailed physical parameters provided by satellite manufacturer Martin Marietta to establish the T30 model for the Block IIR satellite. For the ROCK4, ROCK42, T10, T20 and T30 models, the solar irradiance (formerly known as the solar constant) was taken to be 1 368 W/m².

In recent years, Ziebart et al.[27,28] from University College London have established accurate models for non-conservative forces for handling different types of low-orbit and high-orbit satellites. They further considered the refined three-dimensional model of the satellite and used the ray tracing method to calculate the SRP of each component of the satellite comparing with T20 and T30 model. In this model, the solar irradiance is 1 368 W/m². Since the analytical model cannot fully describe the SRP, Rodriguez-Solano et al.[29] established a semi-empirical and semi-analytical Adjustable Box-Wing model on the basis of Box-Wing by adjusting the optical characteristics of the solar panel and the illuminated panel. In this model, the solar irradiance is 1 367 W/m².

Froideval[30] mentioned that the solar constant was not a constant, and it was a changing sequence of values. He took a solar constant equal to 1 367.2 W/m². Zhao[24] analyzed several factors affecting the accuracy of the SRP models. In the SRP model he established, the solar constant was 1 368 W/m².

2 Solar Irradiance Variance Characteristics and Its Influence on Precision Orbit Determination

In this paper, we use the solar irradiance data of SORCE from the Colorado University to analyze the variance characteristics, and the sampling interval is 6 h. We choose linear interpolation method and segmentation averaging method to calculate the instantaneous solar irradiance and the average solar irradiance of time period, respectively. According to the physical modeling approach of SRP model, we established a variation of solar irradiance SRP model, named as VARSRP, and a segmental average solar irradiance SRP model, named as AVESRP. Then, we take the constant solar irradiance model SRPM[13] to compare the SRP accelerations and the orbit determination accuracy, and investigate its influence on the orbit determination of navigation satellites.

2.1 Solar irradiance variance characteristics investigation

Fig.2 shows the difference sequence between Physikalisch - Meteorologische Observatorium Davos (PMOD) Virgo data (ranging from 30 January, 1996 to 4 February, 2002, with a sampling interval of 1 h), the Colorado SORCE data (ranging from 25 February, 2003 to 11 October, 2018, with a sampling interval of 6 h). The constant value is Φ_0=1 368 W/m^2. The solar irradiance data of Virgo maintain at −4—1 W/m^2, and the data of SORCE is −12—−5 W/m^2. According to the statistical results, the average values of SORCE data changes is −7.093 07 W/m^2, the standard deviation is 0.416 21, and the maximum change value is −11.018 90 W/m^2; the average value of Virgo data changes is −1.283 68 W/m^2. The standard deviation is 0.605 38 and the maximum change −3.322 02 W/m^2. There is a certain gap between the use of the constant calculation and the measured data among the results, so this element should be considered.

Fig.3 shows difference sequence of the neighbor values between PMOD Virgo data (ranging from 30 January, 1996 to 4 February, 2002, with an interval of 1 h) and the Colorado SORCE data (ranging from 25 February, 2003 to 11 October, 2018, with an interval of 6 h), which presents the differences between forward and backward values in these two data sources. The difference between the solar irradiance values is maintained at −1—1 W/m^2. According to the statistical results, the average value of SORCE data changes is −4.608 57e−05 W/m^2, the standard deviation is 0.041 60, and the maximum change value is 1.104 50 W/m^2; the average value of Virgo data change is 1.669 94e−04 W/m^2, the standard deviation is 0.029 84, and the maximum change value is 0.226 51 W/m^2. This confirms that the change in solar irradiance is relatively stable, and the variance range is about 0.1%. At the same time, this also provides a theoretical basis for the selection of interpolation methods for the next solar irradiance modeling.

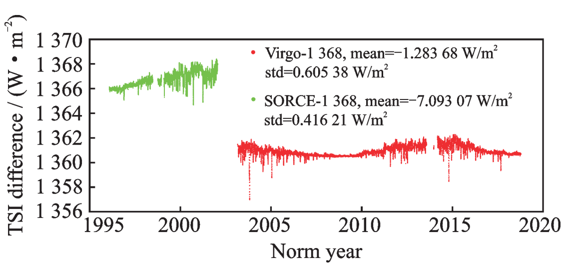

Fig.2 The difference sequence between the PMOD Virgo data and the Colorado SORCE data with the currently used constant solar irradiance values

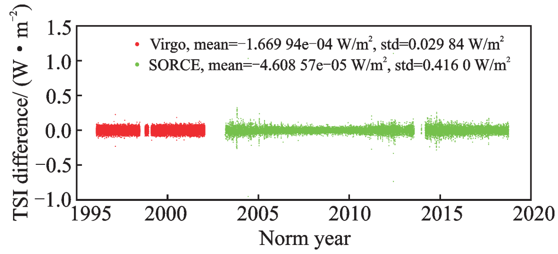

Fig.3 The difference sequence of the PMOD Virgo data and the Colorado SORCE data(the differences between forward and backward)

2.2 Analysis on precision orbit determination for GPS

GPS is the first research object in this study, and it has high precision orbit[31]. We use the global GPS data from Day of Year (DOY) 060 to 149 in 2015, the constant solar irradiance SRP model SRPM (Φ_0=1 368 W/m^2), the variance solar irradiance SRP model VARSRP and the segmental average solar irradiance SRP model AVESRP to perform SRP accelerations and precise orbit determination. Fig.4 shows the difference accelerations of VARSRP and AVESRP comparing with the constant solar irradiance SRP model SRPM (regarding

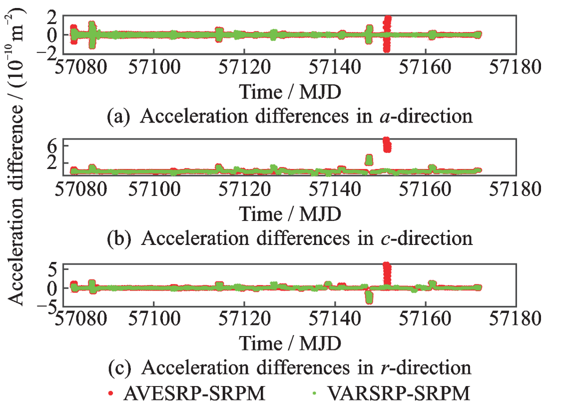

Fig.4 Differences between VARSRP, AVESRP relative to SRPM in three directions including along trace a (top), orbital surface normal c (middle) and radial r (bottom) (regarding the PRN01 satellite as an example)

PRN01 satellite as an example). The SRP acceleration differences of VARSRP and AVESRP relative to SRPM can reach 10^{-10} m/s^2. It means that the error caused by the change in solar irradiance is a factor should be considered when the perturbation magnitude of 10^{-10} m/s^2 is considered.

Figs.5, 6 show the differences in acceleration between different types of GPS satellites using VARSRP, AVESRP model and SRPM model. The VARSRP and AVESRP models are slightly different, but they are more consistent and show common features. The difference between the acceleration of most GPS satellites is up to 10^{-10} m/s^2, and some even reach to 10^{-9} m/s^2, but the difference in average acceleration is relatively small, basically at 10^{-13} m/s^2 magnitude, and mean square error at 10^{-11} m/s^2.

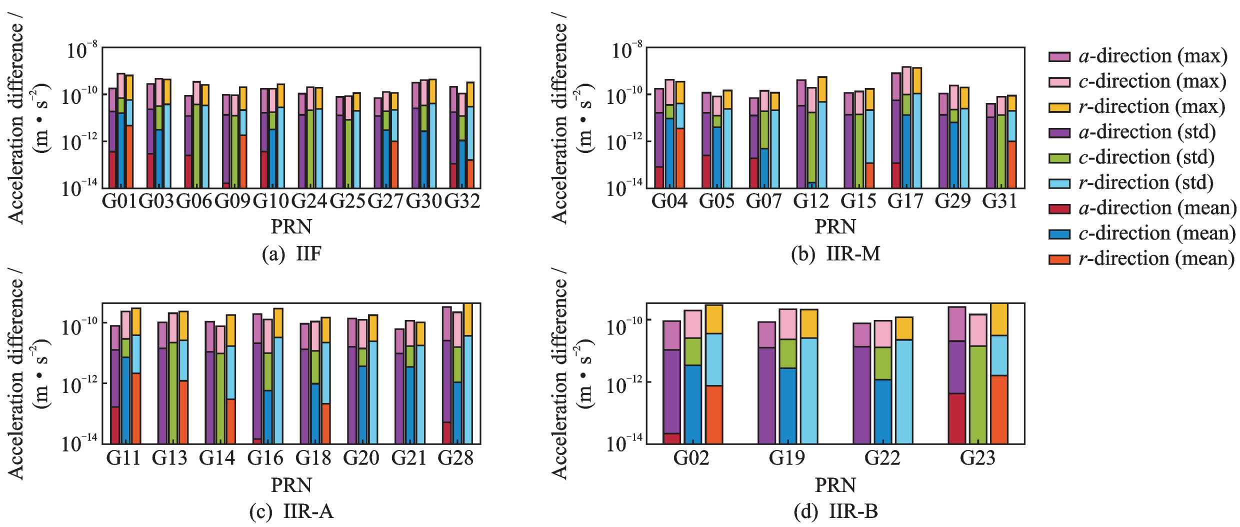

Fig.5 Acceleration difference between AVESRP and SRPM

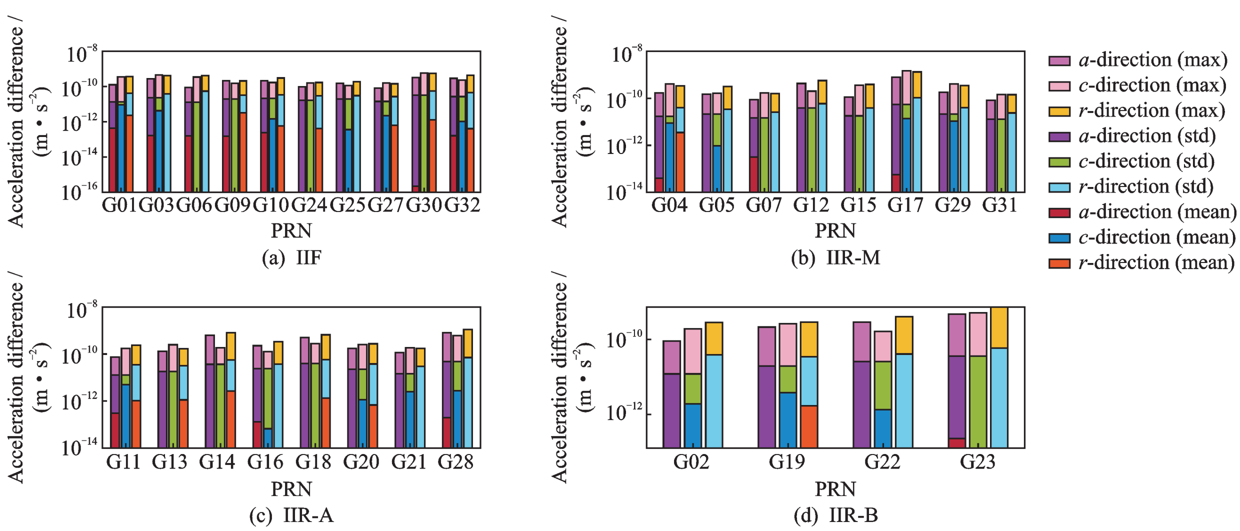

Fig.6 Acceleration difference between VARSRP and SRPM

Fig. 7 illustrates the 3D-RMS values of GPS satellite orbit determination for three different SRP models (SRPM, VARSRP, and AVESRP). The 3D-RMS is obtained from comparing the orbit results with the IGS precision orbit. We choose 30 GPS satellites including IIF, IIR-M, IIR-A and IIR-B to calculate the orbital results. It can be seen from Fig.7 that for most GPS satellites, the AVESRP model and the VARSRP model are slightly improved comparing with SRPM model.

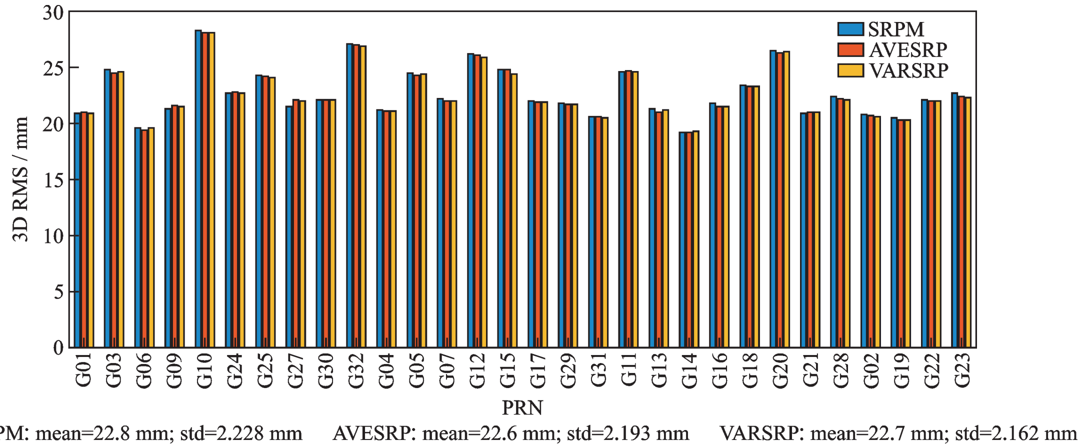

Fig.7 3D-RMS of GPS orbit for the SRPM, VARSRP, and AVESRP

In order to reflect the change of orbital accuracy for the three models of GPS satellites, Table 2 gathers statistics for orbital accuracy of GPS satellites. It implies that the three models have little difference in the orbit determination accuracy of GPS satellites. AVESRP model has 10% (3 satellites) and 17% (5 satellites) satellites unchanged and 70% (21 satellites) and 73% (22 satellites) slightly improved comparing with the SRPM model, and the improvement is about 0.1—0.5 mm. In addition, the variance of solar irradiance has no obvious regularity for the orbit determination accuracy for different types of GPS navigation satellites.

2.3 Precision orbit determination analysis for BDS

BDS is the important research object in this study, and its orbit accuracy is not up to the level of GPS, so more deep research is needed[32]. We used the multi-GNSS experiment (MGEX) network data from DOY 001 to DOY 093 in 2015 for the precision orbit determination. During this period, there are 50—60 stations containing BDS data, and the orbit determination strategy adopted non-difference phase and pseudorange observations with 3 d an arc. Then, three models SRPM (Φ_0=1 368 W/m^2), VARSRP (interpolation Φ_0), and VARSRP (segment average Φ_0) are used to calculate the SRP acceleration and orbit determination accuracy, respectively. We select GEO (C04) IGSO (C06) and MEO (C14) which are representative of different types of BDSs. Fig.8 shows the difference accelerations of VARSRP and AVESRP comparing with the constant solar irradiance SRP model SRPM in three directions, which are along, cross and radial. We can see that the difference reaches 10^{-10} m/s^2.

Fig.9 shows the statistical results of the acceleration difference of VARSRP and AVESRP models relative to the SRPM model. It can be seen that the difference can reach to 10^{-10} m/s^2, and some even reach to 10^{-9}—10^{-8} m/s^2, but the average is relatively small, basically at 10^{-11} m/s^2 magnitude, and the mean square error is around 10^{-11} m/s^2. Moreover, the normal of the orbital plane changes greatly, and some reach 10^{-9} m/s^2. This is greater than the impact of GPS satellites. In addition, in the acceleration changes of the three types of satellites, the GEO satellites change the most; while in the radial direction, along-track and cross-track, the cross-track has the greatest influence. From the view of SRP acceleration for BDS, the solar irradiance should be a necessary factor for noticing.

Table 2 3D-RMS of GPS satellites for three models

Satellite	PRN	SRPM/mm	AVESRP/mm	VARSRP/mm	AVESRP-SRPM/ mm	VARSRP-SRPM/ mm
IIF	G01	20.9	21	20.9	0.1	0.0
	G03	24.8	24.5	24.6	−0.3	−0.2
	G06	19.6	19.4	19.6	−0.2	0.0
	G09	21.3	21.6	21.5	0.3	0.2
	G10	28.3	28.1	28.1	−0.2	−0.2
	G24	22.7	22.8	22.7	0.1	0.0
	G25	24.3	24.2	24.1	−0.1	−0.2
	G27	21.5	22.1	22	0.6	0.5
	G30	22.1	22.1	22.1	0.0	0.0
	G32	27.1	27	26.9	−0.1	−0.2
	mean	23.3	23.2	23.2	−0.1	−0.1
IIR-M	G04	21.2	21.1	21.1	−0.1	−0.1
	G05	24.5	24.3	24.4	−0.2	−0.1
	G07	22.2	22	22	−0.2	−0.2
	G12	26.2	26.1	25.9	−0.1	−0.3
	G15	24.8	24.8	24.4	0.0	−0.4
	G17	22	21.9	21.9	−0.1	−0.1
	G29	21.8	21.7	21.7	−0.1	−0.1
	G31	20.6	20.6	20.5	0.0	−0.1
	mean	23	22.8	22.7	−0.2	−0.3
IIR-A	G11	24.6	24.7	24.6	0.1	0.0
	G13	21.3	21	21.2	−0.3	−0.1
	G14	19.2	19.2	19.3	0.0	0.1
	G16	21.8	21.5	21.5	−0.3	−0.3
	G18	23.4	23.3	23.3	−0.1	−0.1
	G20	26.5	26.3	26.4	−0.2	−0.1
	G21	20.9	21	21	0.1	0.1
	G28	22.4	22.2	22.1	−0.2	−0.3
	mean	22.5	22.4	22.4	−0.1	−0.1
IIR-B	G02	20.8	20.7	20.6	−0.1	−0.2
	G19	20.5	20.3	20.3	−0.2	−0.2
	G22	22.1	22	22	−0.1	−0.1
	G23	23.7	23.4	23.3	−0.3	−0.4
	mean	21.7	21.6	21.5	−0.1	−0.2

Fig.10 shows the 3D RMS statistics analysis for three types of BDS satellites about orbital overlapping arc. Fig.11(a) shows all BDS satellites orbit determination accuracy differences of the AVESRP and VARSRP relative to SRPM. Table 3 gives the 3D-RMS values of the overlapping arc for the three models of BDS satellites. Fig.11(b) shows the RMS value of the BDS orbital residual. It can be seen that the accuracy of orbit determination with AVESRP and VARSRP is more obvious for GEO satellites, and the improvements are 3.5 mm and 4.0 mm, respectively. The VARSRP is slightly better than the AVESRP model, especially for the accuracy of the C05 satellite. But both models perform poorly for C03, and the reasons for this need to be further studied. For IGSO and MEO satellites, the accuracy of the three models is not much different. This may be due to the higher orbit of GEO satellites, which is more affected by changes in solar irradiance. In addition, according to the statistics of the daily orbital accuracy of SRPM for all satellites of the BDS, the accuracy of the orbit determination of

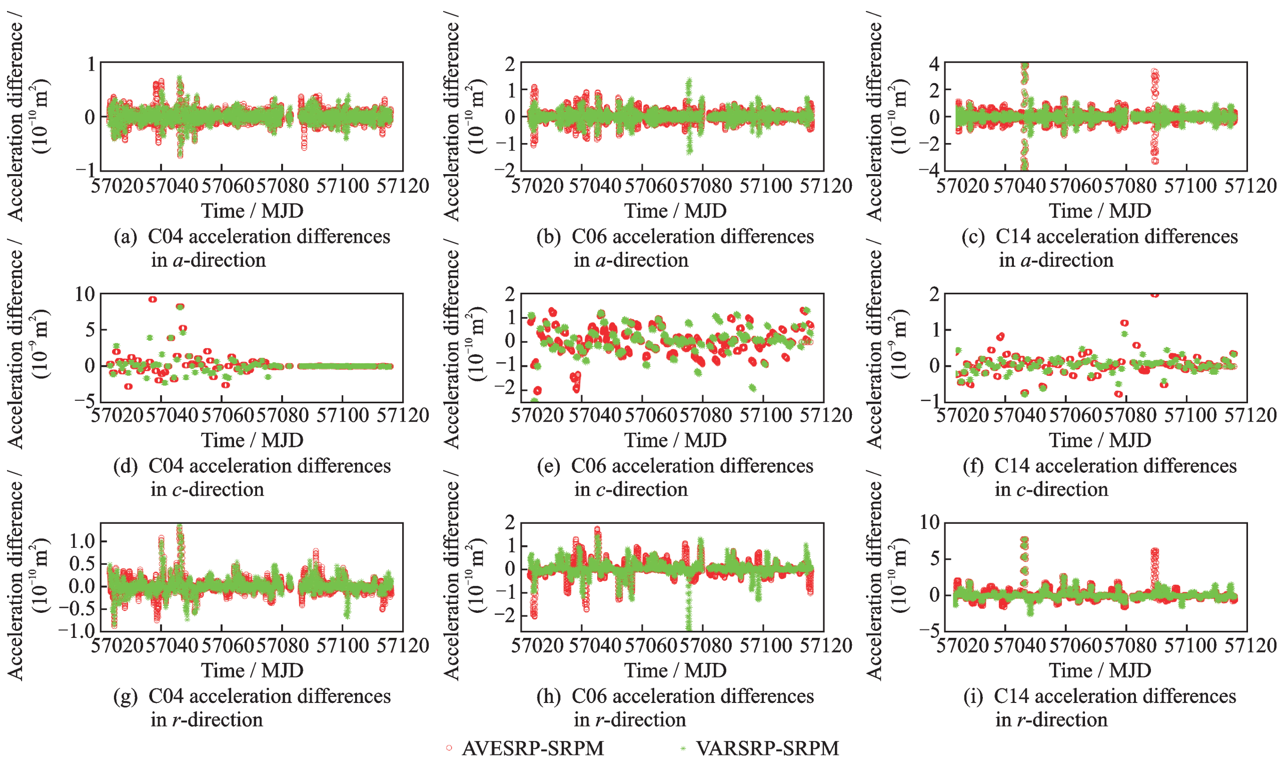

Fig.8 Differences between of VARSRP, AVESRP and constant solar irradiance SRP model in three directions including along trace *a* (top), orbital surface normal *c* (middle) and radial *r* (bottom) (C04, C06, C14)

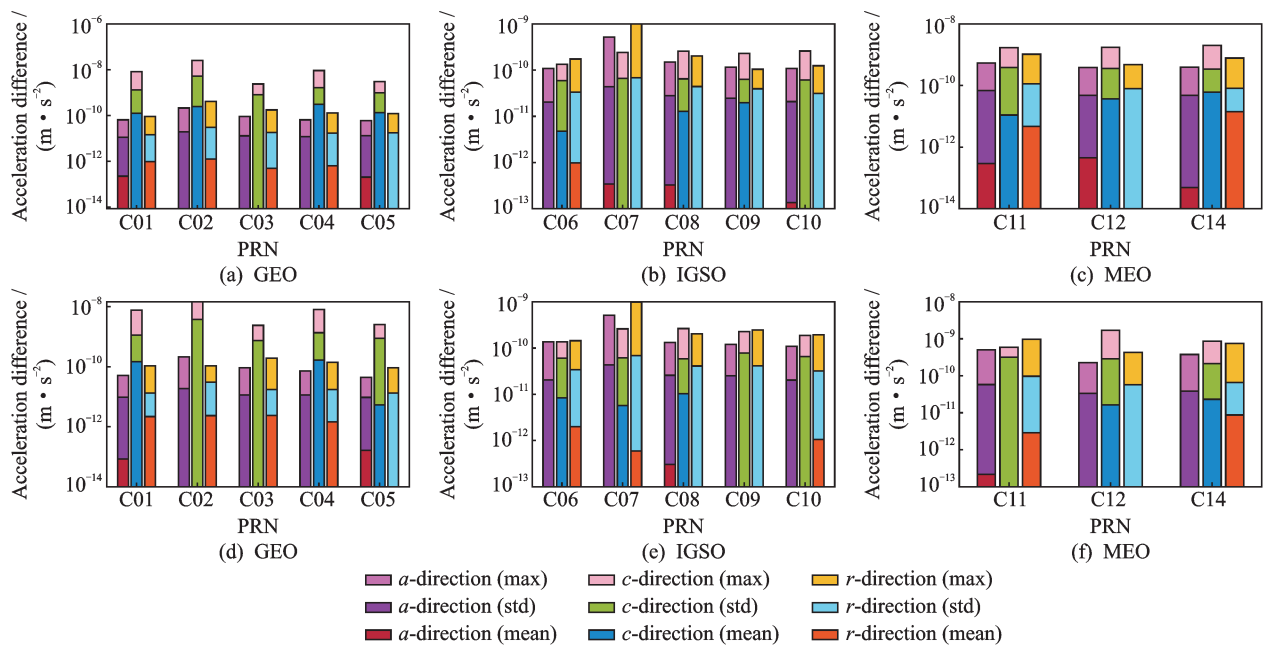

Fig.9 Acceleration differences of VARSRP and SRPM (top), AVESRP and SRPM (bottom)

67% and 69% is improved, respectively. From the view of precision orbit determination, solar irradiance is an important element for BDS.

In order to more reliably evaluate the effects of BDS three different solar irradiances SRP models on the orbit determination, this paper uses the normal point (NP) data of the satellite laser ranging (SLR) from the international laser ranging service (ILRS) to check the orbit determination accuracy externally. There were C01, C08, C10, and C11 satellites with laser observations in 2015. The full rate data are used as reference and supplement to

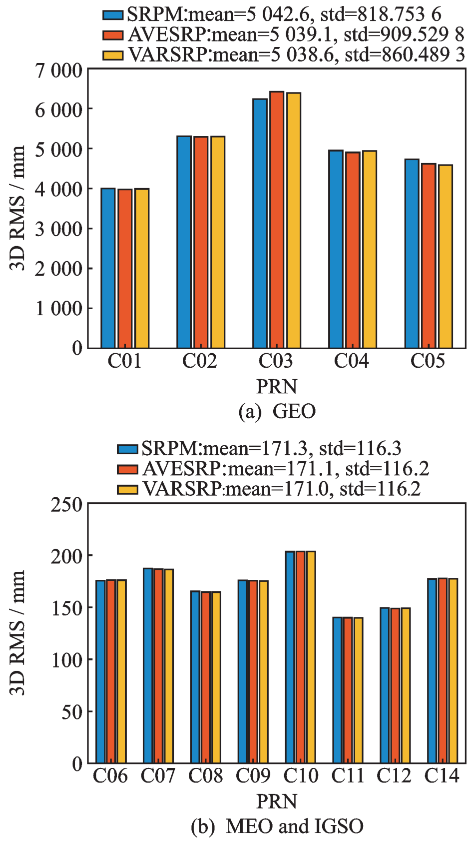

Fig.10 Average 3D-RMS values of BDS satellites overlapping arc

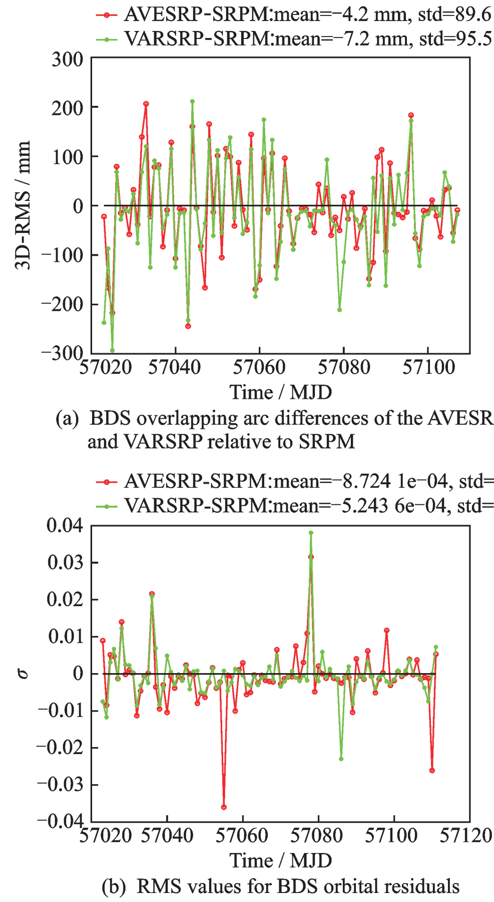

Fig.11 Average 3D-RMS values of satellites overlapping arc differences and the RMS values for BDS orbital residuals

check results. Since the C08 and C11 data are less, we choose C01 and C10 to gather statistics. The results of C01 and C10 SLR check are given in Fig.12. It can be seen that the orbital accuracy of C01 using the AVESRP model and the VARSRP model is improved by 2.3 mm and 3.5 mm, respec-

Table 3 3D-RMS values of the overlapping arc for the three models of BDS satellite

Satellite	PRN	SRPM/mm	AVESRP/mm	VARSRP/mm	AVESRP-SRPM/ mm	VARSRP-SRPM/ mm
GEO	C01	3 997.3	3 972.5	3 987.2	−24.8	−10.1
	C02	5 303.7	5 288.4	5 299.4	−15.3	−4.3
	C03	6 232.1	6 420.7	6 387.2	188.6	155.1
	C04	4 948.2	4 900.4	4 935.8	−47.8	−12.4
	C05	4 731.5	4 613.5	4 583.5	−118.0	−148.0
	mean	5 042.6	5 039.1	5 038.6	−3.5	−4.0
IGSO	C06	175.5	176.1	176.0	0.6	0.5
	C07	187.3	186.5	186.3	−0.8	−1.0
	C08	165.2	164.6	164.6	−0.6	−0.6
	C09	175.9	175.6	175.2	−0.3	−0.7
	C10	203.4	203.6	203.5	0.2	0.1
	mean	181.5	181.3	181.1	−0.2	−0.4
MEO	C11	140.2	140.0	139.8	−0.2	−0.4
	C12	149.3	148.8	149.0	−0.5	−0.3
	C14	177.2	177.6	177.5	0.4	0.3
	mean	155.6	155.5	155.4	−0.1	−0.2

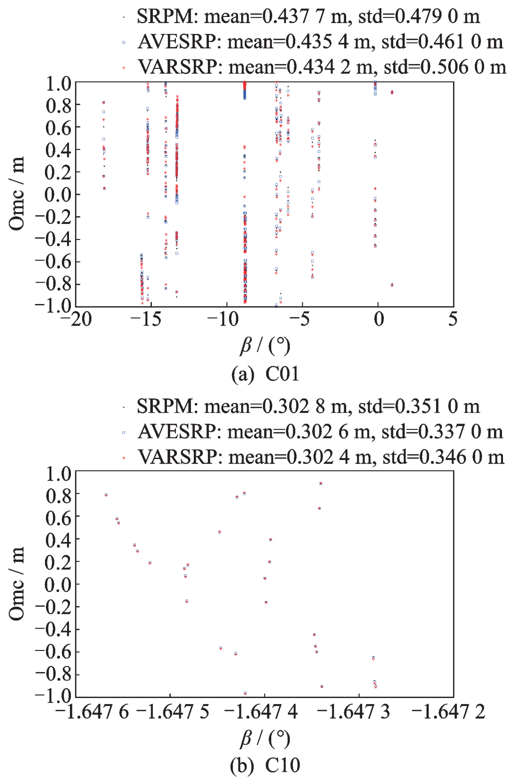

Fig.12 SLR check results for BDS satellites

tively, and C10 has been improved by 0.2 mm and 0.4 mm, respectively.

3 Conclusions

This paper firstly analyzes the physical mechanism that the "solar constant" is not constant. We start with the research status and theoretical introduction of solar irradiance, then use the spatial measurement data to analyze the variance characteristics of solar irradiance. Next, as for GPS and BDS navigation satellites, we use measured data to construct different types of SRP models including SRPM (Φ_0=1 368 W/m^2), VARSRP and AVESRP, and we use these three models to calculate and compare SRP acceleration and orbit determination accuracy. The results show that the SRP acceleration differences of VARSRP and AVESRP relative to SRPM can reach 10^{-10} m/s^2, and some satellites even reach 10^{-8} m/s^2, but the difference in average acceleration is relatively small, at the magnitude of 10^{-11} m/s^2, and the mean square error is around 10^{-11} m/s^2. In addition, the changes are relatively large in cross-trace, and some can reach 10^{-9} m/s^2.

The three models have little difference in the orbit accuracy of GPS satellites in totally. Compared with the SRPM model, the AVESRP and VARSRP have 10% (3 satellites) and 17% (5 satellites) unchanged respectively, 70% (21 satellites) and 73% (22 satellites) have a slight improvement, and the increase range is 0.1—0.5 mm. Moreover, there is no obvious regularity for the orbit determination accuracy of different types of GPS navigation satellites. For the GEO satellites of BDS, the accuracy of orbit by AVESRP and VARSRP is obviously improved. But for IGSO and MEO satellites, the accuracy differences of the three models are small. This may be due to the higher orbit of GEO satellites, which is more affected by changes in solar irradiance. The statistics of the BDS daily orbital accuracy for all satellites of AVESRP and VARSRP models have 67% and 69% improved.

In conclusion, when we consider the magnitude of 10^{-10} m/s^2, the error caused by the change of solar irradiance is a factor that must be considered. In addition, high-precision navigation satellites precise orbit determination, especially for satellites with accuracy requirements are better than 2 cm, need to consider the influence of the solar radiation force caused by the change in solar irradiance. It is recommended that the solar irradiance obtained from satellite measurements should be used to model solar radiation pressure.

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Acknowledgements This work was supported by the National Key Research and Development Program of China (No.2016YFB0501405), the National Natural Science Foundation of China (No.11973073), the Basic Project of Ministry of Science and Technology of China (No. 2015FY310200), and the Shanghai Key Laboratory of Space Navigation and Position Techniques (No.06DZ22101).

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Competing interests The authors declare no competing interests.

(Production Editor: Zhang Bei)