The Data Comparison of Electron Density Between CSES and DEMETER Satellite, Swarm Constellation and IRI Model

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Abstract The China Seismo-Electromagnetic Satellite (CSES), which is also called ZhangHeng-1 (ZH-1), was successfully launched on February 2, 2018. Evaluating the quality of observation data is imperative for the satellite mission and users. Through the comparative analysis of electron density between CSES and DEMETER satellite, Swarm constellation and international reference ionosphere (IRI) model from May 8, 2018 to December 31, 2019, it was found that the patterns of electron density for CSES are similar with those of other observations and model outputs, such as the maxima and minima nearly locating in the same place, having the ionospheric phenomena of wave number 3/4, electron density enhancements at mid-latitude, and Weddell Sea Anomaly (WSA). The correlation coefficients are higher in the Southern Hemisphere, especially in the region of WSA. The correlation between CSES and IRI model is also better around the equatorial ionization anomaly crests during the daytime, while the correlation coefficients are low around the magnetic equator for the Ne single peak detected by CSES. Comparing the observation data in orbit during the same time, the correlation coefficients between CSES and Swarm constellation all exceed 0.75, the curves of nearby orbits exhibiting the consistent peaks or troughs around the roughly same latitudes. Nevertheless, there are systematic biases in the values between the electron density data of CSES and other observations/models, 1–2 times and over two times lower than IRI model during the nighttime and daytime, respectively. The electron density values of Swarm constellation are 3–6 times greater than those of CSES according to the data statistics of nearby orbits. We considered that both hardware design and data processing may potentially have effects on the Ne systematic biases between the CSES and other observations. Through the comparative analysis, it is concluded that the electron density observed by CSES can exhibit the ionospheric characteristics at the altitude of 507 km, and the data can be applied to the ionospheric phenomena study.

1. Introduction

The ionosphere was discovered in 1901 when Marconi successfully transmitted radio signals across the Atlantic (Lodge, 1902). In 1902, the first physical theory of the ionosphere was proposed (Lodge, 1902). Appleton and Barnett (1925) and Breit and Tuve (1925), using radio wave sounding methods, confirmed the ionosphere’s existence in the high atmosphere at nearly the same time in 1924. This confirmation signaled the beginning of ionospheric studies.

In general, ionospheric measurement techniques can be categorized into two types, remote sensing and direct (in situ) observation (Schunk & Andrew, 2009; Xiong et al., 1999). The former one includes vertical sounding, oblique sounding, oblique backscatter sounding, radio occultation, incoherent scatter radar, and laser radar. The latter one involves satellite and rocket sounding. Among these measurement techniques, the observation range of satellite sounding could cover the whole world, which is useful to investigate the ionospheric phenomena.

The China Seismo-Electromagnetic Satellite (CSES), which is also called ZhangHeng-1 (ZH-1), was successfully launched on February 2, 2018. CSES can provide global data of the electromagnetic field, plasma and energetic particles to monitor and study the physical phenomena in the ionosphere (Shen, Zhang, et al., 2018). Before the scientific study, the quality of the observation data is concerned by most of the researchers (Lomidze et al., 2017; McNamara et al., 2007; Pedatella et al., 2015). As the observation accuracy of parameters in the ionosphere cannot be directly checked, the comparison with other observations or...
models is the key way to evaluate the quality of the data. Wang et al. (2019) compared the electron density (Ne) of CSES with that of Swarm satellites, and found the high consistency between the two datasets. While the time range of CSES data in their study just covers 7 months, also including in-orbit testing phase. To our knowledge, the more data are analyzed, the more credible comparison is. Yan et al. (2020) used the long time data to compare the Ne and Te (electron temperature) global distributions of CSES and Swarm B satellite. The well-known reliably ionospheric data from Incoherent Scatter Radars (ISRs) were also applied in Yan et al. (2020) study, while there were only 22 events, which is too few to evaluate the Ne quality of CSES. Furthermore, the empirical model data were accepted to enlarge the datasets, while they just concerned the data of revisiting orbits passing by Millstone Hill, not the observation data in the whole world. In a word, although the Ne comparative analyses between CSES and other observations/models have been carried out by Wang et al. (2019) and Yan et al. (2020), the data analysis is also needed from different aspects, including different observations, long time data, and more regions. In our study, in order to identify the data quality of electron density observed by CSES, model outputs and other observations are applied to carry out the comparative research, including the Detection of Electro-Magnetic Emissions Transmitted from Earthquake Regions (DEMETER) satellite which is not used in the works of Wang et al. (2019) and Yan et al. (2020), Swarm constellation (including Swarm A, B, and C satellites) and international reference ionosphere (IRI) model. Furthermore, all the comparative analyses are not just for some areas but for the global regions.

2. Data Introduction

CSES is a circular Sun-synchronous satellite with an orbital inclination of 97.4°. The altitude of this satellite is about 507 km, and the descending and ascending nodes are 14:00 LT (local time) and 02:00 LT, respectively. As the orbit of CSES is strictly revisited each 5 days, the global electromagnetic environment in the ionosphere can be obtained every 5 days. Eight scientific payloads are equipped on CSES (Shen, Zong, et al., 2018), including a High Precision Magnetometer (HPM), an Electric Field Detector (EFD), a Search Coil Magnetometer (SCM), a Plasma Analyzer Package (PAP), a Langmuir Probe (LAP), a High Energetic Particle Package (HEPP) and High Energetic Particle Detector (HEPD), a GNSS Occultation Receiver (GOR) and a Tri-Band Beacon (TBB).

In this study, we paid attention to the data of electron density observed by LAP. The Ne measurement range of CSES LAP is $5 \times 10^2$–$1 \times 10^7$ cm$^{-3}$ with the relative accuracy of 10% (Liu et al., 2019). Two sensors are equipped on the LAP payload. The sensor 1 is a larger one with the diameter of 5 cm, and the diameter of sensor 2 is 1 cm, designed as a backup. In this work, the data we used are observed by sensor 1. There are two operation modes for the CSES, including survey and burst modes. When the satellite flies over China, the Circum-Pacific and Eurasia seismic belts, the burst mode will be automatically triggered with a higher resolution (Shen, Zong, et al., 2018). For LAP payload, the time resolutions of survey and burst modes are 3 and 1.5 s, respectively. The electron density data observed by CSES can be downloaded from the website http://www.leos.ac.cn/ after the registration. Except for the data of in-orbit testing in the first three months, the Ne data from May 8, 2018 to December 31, 2019 were collected to carry out the comparative study.

3. Results

3.1. Comparing Analysis with DEMETER Satellite

DEMETER satellite was launched on June 29, 2004 and stopped receiving data on December 9, 2010, which means the observation data can cover almost 6.5 years. This satellite also flies at a Sun-synchronous, nearly polar orbit, and passes over a given region twice per day, at 10:30 LT and 22:30 LT (Cussac et al., 2006; Parrot, 2012). There is a little difference at the altitude between CSES and DEMETER satellite. DEMETER satellite was launched at altitude 710 km, and declined to 670 km in mid-December 2005 (Zhang, 2014). The Ne data of the ionosphere are also observed by Langmuir probe installed on DEMETER satellite, with a 1 s time-resolution (Lebreton et al., 2006).

The solar 10.7 cm radio flux ($F_{10.7}$) indices during 23rd and 24th solar cycles (showing in Figure 1) exhibit that the index data between 2007–2008 and 2018–2019 were almost same for the 11-year solar cycle. Therefore, the electron density data observed by CSES during 2018–2019 can be compared with those observed by
DEMETER satellite during 2007–2008. Furthermore, the discrepancy between the two data may be less in the period of solar minimum, which is useful to carry out the comparative analysis.

Ne data of CSES and DEMETER satellite were divided into three seasons to compare the variation. According to the Lloyd criteria (Lloyd, 1861), the months of winter for the Northern Hemisphere include November, December, January, and February, and equinox covers March, April, September, and October, and summer contains the months of May, June, July, and August. Based on the local time, the observation data were separated into two groups, the day and night sides. The median values are applied to represent the observation data that fall into each 2.5° (latitude) × 5° (longitude) grid.

Figures 2 and 3 exhibit the Ne distributions of CSES in 2018, 2019 (left panels) and DEMETER satellite in 2007, 2008 (right panels) during nighttime, the top, middle and bottom panels for equinox, summer and winter. There is no observation datum at the magnetic latitudes above ±65° for DEMETER satellite. The Ne pattern of CSES is completely the same as that of DEMETER satellite during nighttime. In the equinox, although the wave number 4 (WN4) structure of electron density for CSES is less obvious than that for DEMETER satellite, there is still wave number 3 (WN3) pattern around the magnetic equator region. In the summer, the Ne distribution of the two satellites can be divided into two parts from the longitude of 60°W. In one region with the longitude from 60°W to 180°W, the maxima locate around the magnetic equator, and high values can be also found in the areas with the magnetic latitude 30°–50° in both hemispheres. In another region with the longitude from 60°W to 180°E, the data values around the magnetic equator are low, and the electron density around the magnetic latitude ±30°–±50° has high value, especially in the longitude 110°E–180°E. Electron density enhancements at mid-latitude have been reported in many studies (e.g., Liu et al., 2011; Luan et al., 2008; Xiong et al., 2019). Based on the characteristics and patterns of this phenomenon, it can be called Mid-latitude Summer Nighttime Anomaly (MSNA) (Chen et al., 2012; Hsu et al., 2011), Mid-latitude arcs (MLA) (Zhang et al., 2013) and Middle-latitudinal band structure (Zhong et al., 2019). Through the analysis of in-situ electron density measurements by the CHAllenging Minisatellite Payload (CHAMP) and the Defense Meteorological Satellites Program (DMSP) F17 satellites, Li et al. (2018) gave out that the location of the enhancements is between magnetic latitude ±30° and ±50°, which is well consistent...
In the winter, the location of observation maximum for the two satellites is almost between the magnetic equator and magnetic latitude 20°S. Besides that, the high values locating in the region from southern Pacific Ocean to southern Atlantic Ocean are also obvious for CSES and DEMETER satellite. This phenomenon is called the Weddell Sea Anomaly (WSA), appearing in the evening during local summer (Bellchambers & Piggott, 1958; He et al., 2009; Penndorf, 1965), and the WSA location is around longitude 150°W–20°W and latitude 40°S–70°S obtained by Zakharenkova et al. (2017) based on the GPS TEC analysis.

Figure 2. The Ne distributions of CSES in 2018 (left panel) and DEMETER satellite in 2007 (right panel) during the nighttime. The seasons of each panel from top to bottom are equinox, local summer and winter for the Northern Hemisphere. The detailed months for each subplot are marked on the top. The red lines represent magnetic latitudes by 30° interval, with the detailed values in the top panels. CSES, China Seismo-Electromagnetic Satellite.

Figure 3. The Ne distributions of CSES in 2019 (left panel) and DEMETER satellite in 2008 (right panel) during the nighttime. The illustration is same as Figure 2. CSES, China Seismo-Electromagnetic Satellite.
The Ne distributions of CSES and DEMETER satellite in the daytime are shown in Figures 4 and 5. In general, the Ne pattern of CSES is similar with that of DEMETER satellite. The high values almost locate around the magnetic equator in the equinox, and the banding distribution of the maximum is shifting to the Northern and Southern Hemispheres for the local summer (middle panels) and winter seasons (bottom panels), respectively. Wave number 4/3 patterns can be detected around the magnetic equator for CSES and DEMETER satellite.

**Figure 4.** The Ne distributions of CSES in 2018 (left panel) and DEMETER satellite in 2007 (right panel) during the daytime. The illustration is same as Figure 2. CSES, China Seismo-Electromagnetic Satellite.

**Figure 5.** The Ne distributions of CSES in 2019 (left panel) and DEMETER satellite in 2008 (right panel) during the daytime. The illustration is same as Figure 2. CSES, China Seismo-Electromagnetic Satellite.
The median datum in each 10° (latitude) × 60° (longitude) grid is obtained for every day to analyze the Ne variation trend in the time series. Taking the longitude 0°W–60°W as an example, the time series of electron density in the nighttime from May 8, 2018 to December 31, 2019 are shown in Figure 6a, blue and red lines representing the Ne data of CSES and DEMETER satellite. Furthermore, the correlation coefficients of electron density for the two satellites were also calculated according to the Equation 1.

\[
R(i, j) = \frac{C(i, j)}{\sqrt{C(i, i)C(j, j)}},
\]

(1)

C means covariance matrix, and \(i, j\) represent Ne data in each day for CSES and DEMETER satellite. The correlation coefficients between the two series data and latitudinal ranges are marked on the top of each subplot in Figure 6a. The Ne patterns of CSES and DEMETER satellite are similar at different latitudes, with high values in the local summer and low values in the local winter of Southern Hemisphere and high latitude of Northern Hemisphere. Figure 6b exhibits a larger version at geographical latitude 30°S–40°S, longitude 0°W–60°W in the nighttime. The blue and red lines represent Ne data observed by CSES and DEMETER satellite, respectively. CSES, China seismo-electromagnetic satellite.
coefficients in the whole world during the nighttime (left panel) and daytime (right panel), respectively. In general, the correlation coefficients in the magnetic Southern Hemisphere are better than those in the magnetic Northern Hemisphere, especially during the daytime. The correlation coefficients in the south of the Atlantic Ocean are almost over 0.5 for both nighttime and daytime. The electron density around the magnetic equator varies strongly due to the direct solar ionization effect in different years, which may be the main reason for the low values around the magnetic equator during daytime.

3.2. Comparing Analysis with IRI Model

The IRI is an internationally recognized and recommended standard for the specific plasma parameters in the Earth’s ionosphere, based on available data sources, including the worldwide network of ionosondes, the powerful incoherent scatter radars, the Innovative Solutions In Space (ISIS) and Alouette topside sounders, and in situ instruments flown on many satellites and rockets (Bilitza et al., 2011). As the offline source codes of IRI 2016 model are supported, we adopted this version in our study, which is available at http://irimodel.org/. For the given location, time and date, IRI model can provide the electron density, electron temperature, ion temperature, and ion composition in the ionospheric altitude range. In order to carry out the comparing analysis, the grid (2.5° × 5°) outputs of electron density at the CSES altitude (507 km) were obtained by IRI 2016 empirical model at 14:00 (LT) and 02:00 (LT) from May 8, 2018 to December 31, 2019.

Same as the comparison with the DEMETER satellite, the Ne median values were calculated in each grid for the equinox, summer and winter seasons, and the Ne distributions are shown in Figures 8, 9, 10, and 11 for CSES (left panels) and IRI model (right panels) in 2018 and 2019. In general, although the model data are smoother than the observed data, the patterns of CSES are similar with IRI outputs in different seasons and years. During the nighttime (Figures 8 and 9), high values of the two data in the equinox all locate around the magnetic equator and the region with magnetic latitude ±30°–±50°, especially in the south of the Pacific Ocean. In the summer, low values of observation and model data appear around the magnetic equator at the longitude 60°W–180°E. The high values of IRI outputs exhibit the banded characteristics along the magnetic latitude 20°–40° in the Northern Hemisphere. The regions of maximal data for CSES mainly situate around the magnetic equator at the longitude 60°W–180°E and in the region of magnetic latitude ±30°–±50° from 110°E to 60°W. The enhancements at mid-latitude along the longitude 120°E–180°E of CSES are more obvious than those of IRI model, which may suggest that extra plasmas in the ionosphere provided by the plasmasphere through downward plasma influx along the magnetic field lines (Li et al., 2018) are more in this region for CSES observation. In the winter, the WSA phenomenon is both found in CSES and IRI model. The region of maxima for IRI model is broader than that for CSES. Furthermore, the electron density in 2019 enhanced compared with that in 2018 both for CSES and IRI model, which reflects the consistency of the two datasets.

During the daytime (Figures 10 and 11), the phenomenon of equatorial ionization anomaly (EIA) is obvious for the IRI outputs due to the $E \times B$ plasma drift (Ratcliffe, 1972), with the electron density decreasing at
The magnetic equator and enhancing at its each side. The values of the EIA crest in the local summer hemisphere are higher than those in the local winter hemisphere for IRI outputs. The maxima of CSES locate around the magnetic equator in equinox, while the trough at the magnetic equator reflecting in IRI model is not observed. The EIA crest of CSES also exists in the local summer hemisphere, whereas another side peak in the local winter hemisphere is not obvious.

The time series of electron density for the observation and model data were also analyzed in different longitudinal and latitudinal regions from May 8, 2018 to December 31, 2019. Same as the comparison of

Figure 8. The Ne distributions of CSES (left panels) and IRI model (right panels) during the nighttime in 2018. The illustration is same as Figure 2. CSES, China seismo-electromagnetic satellite; IRI, international reference ionosphere.

Figure 9. The Ne distributions of CSES (left panels) and IRI model (right panels) during the nighttime in 2019. The illustration is same as Figure 2. CSES, China seismo-electromagnetic satellite; IRI, international reference ionosphere.
DEMETER satellite, the analysis at the longitude 0°–60°W in the nighttime is taken as an example (Figure 12), blue and red lines representing the electron density of CSES and IRI model. The variation trends of the two data are almost same for most of the latitudinal regions, with the peak and trough in local summer and winter, respectively. The correlation coefficients between the two data were calculated by Equation 1, which are marked on the top of each subplot. All the correlation coefficients in the Southern Hemisphere are above 0.75, and the data in the Northern Hemisphere are more than 0.4 except the middle latitudinal regions.

Figure 10. The Ne distributions of CSES (left panels) and IRI model (right panels) during the daytime in 2018. The illustration is same as Figure 2. CSES, China seismo-electromagnetic satellite; IRI, international reference ionosphere.

Figure 11. The Ne distributions of CSES (left panels) and IRI model (right panels) during the daytime in 2019. The illustration is same as Figure 2. CSES, China seismo-electromagnetic satellite; IRI, international reference ionosphere.
The comparison between CSES and IRI model was carried out in the whole world by calculating the correlation coefficient in each 2.5°(latitude) × 5°(longitude) grid, based on the Ne data from May 8, 2018 to December 31, 2019. Figure 13 exhibits the correlation coefficients in the global regions during the nighttime (left panel) and daytime (right panel). In the night side, the values in the Southern Hemisphere are higher than those in the Northern Hemisphere, especially around the South Atlantic Ocean region. The Ne correlation between CSES and IRI model at the high latitude is also better for the two hemispheres. During the daytime, low values appear around the magnetic equator and the high latitude in the Northern Hemisphere. The correlation coefficients in the location of EIA crests and South Atlantic Ocean have high values, almost exceeding 0.5.

As showing in Figure 12, the Ne values of CSES are lower than those of IRI model. In order to quantitatively compare the data values, the ratios of Ne data between IRI model and CSES were obtained in each 2.5°
(latitude) × 5° (longitude) grid, showing in Figure 14. In the nighttime (left panel of Figure 14), the roughly equal values just appear in the region of southern Indian Ocean and magnetic low latitude along the longitude 100°W–180°W. The Ne data of IRI model are almost 1–2 times higher than those of CSES, except the region of magnetic high latitude with the ratio almost exceeding 5. The differences between the two data are greater during the daytime (right panel of Figure 14), as all the ratios are over 3. Furthermore, the ratios between model and observation data are more than 10 times in the locations of Northern Hemisphere and southern Pacific Ocean.

3.3. Comparing Analysis with Swarm Constellation

Swarm constellation is the European Space Agency (ESA) satellites, including three identical quasipolar orbit satellites (Friis-Christensen et al., 2006), Swarm A and Swarm C at the lower altitude orbit (around 460 km), and Swarm B at the higher altitude orbit (around 510 km). These satellites were launched on November 22, 2013 and are still orbiting around the Earth. The in situ data of electron density are also observed by the payload of Langmuir probe on Swarm satellites with a time resolution of 2 Hz (Knudsen et al., 2017; Xiong et al., 2016). The similar altitude and same observation parameter with CSES provide a choice to carry out the comparison study.

If the numbers of observation points for each CSES orbit meeting the following two criteria are more than 50, the nearby data of CSES and Swarm constellation are selected to carry out the comparison: (1) for the time criterion, the universal time that is accurate to minute must be same for observation points of CSES and Swarm constellation; (2) for the location criterion, the differences between the two datasets at the longitude and latitude are both less than 5°. Through the search in the two datasets, 883, 813 and 1,019 nearby orbits between CSES and Swarm A, B, and C satellites were collected during the time period of May 8, 2018 to December 31, 2019. Looking over the data of nearby orbits, it is found that the patterns of electron density along the latitude are almost same (two examples shown in Figure 15), not only the higher altitude satellite (left panel for Swarm B) but also the lower altitude satellite (right panel for Swarm C). Furthermore, some subtle variations are even similar for the two data, exhibiting the simultaneous peaks or troughs around the roughly same latitudes. The correlation between the CSES and Swarm constellation was analyzed at the latitudes (with the 0.1° accuracy). The scatters of nearby orbits at almost same latitudes are shown in Figure 16, X and Y axes representing Swarm constellation and CSES, and the coefficients calculated according to Equation 1 are 0.7521, 0.8114, and 0.7646 for Swarm A, B and C, respectively. The two data are strongly correlated, especially for Swarm B satellite, the nearest one to the CSES orbit altitude. The correlation coefficients along the latitudes by 1° interval were obtained for Swarm A, B and C satellites, showing in Figure 17. Consisting with the results of DEMETER satellite and IRI model, the coefficients in the Southern Hemisphere and at the low and mid-high latitudes in the Northern Hemisphere have high values, while the data around latitude 30° in the Northern Hemisphere are relatively low. Furthermore, the empirical equations obtained by linear fitting were given out based on the observation data of nearby orbits between CSES and Swarm constellation, Equations 2, 3 and 4 for Swarm A, B, and C satellites, respectively.
\[ y = 0.14 \times x + 1.12 \times 10^9 \]  
\[ y = 0.19 \times x - 1.15 \times 10^9 \]  
\[ y = 0.14 \times x + 1.34 \times 10^9 \]

where \( x \) and \( y \) represent the \( N_e \) data of Swarm constellation and CSES, respectively.

It can be found that in Figure 15 the \( N_e \) values of CSES are also lower than those of Swarm constellation. In order to quantificationally evaluate the values, the \( N_e \) ratios between Swarm constellation and CSES at the same latitude for nearby orbits were obtained. The histograms of these ratios are shown in Figure 18, left, middle and right panels for Swarm A, B and C satellites, respectively. Although there are differences among the subplots, the probabilities of ratio 4–7 all exceed 10%, which means that most of \( N_e \) values for CSES are 3–6 times lower than those of Swarm constellation.

### 3.4. Simultaneous Variations with CSES Other Parameters

What makes CSES as a fantastic mission to improve our knowledge of near-Earth space is the simultaneous measurements of different parameters. As introducing in Section 2, there are eight payloads equipped...
on CSES, including the observation parameters of electromagnetic field, plasma and energetic particles. To our knowledge, there will be simultaneous variations of ionospheric parameters responding to a spatial event, such as solar activity, magnetic storm and substorm. A magnetic storm occurred on August 26, 2018, the $Dst$ index reaching to $-174$ nT. Focusing on this event, multiple parameters observed by EFD, LAP and PAP of CSES for an ascending orbit on August 26, 2018 were shown in Figure 19. The panels from top to bottom represent orbit position, very low frequency electric field spectrum, electron density, electron temperature, ion density and ion temperature. It can be seen that the electron density observed by Langmuir probe simultaneously varied with other parameters at the middle and high latitudes in the Southern and Northern Hemispheres. Simultaneous variations with other parameters of CSES also verify the authenticity and reliability of electron density observed by Langmuir probe.

4. Discussions

Through the comparative analysis, the global distributions of electron density observed by CSES are consistent with the observations of DEMETER satellite and the outputs of IRI model. In the nighttime, the structure of wave number 3 is more obvious for the CSES observation, while the electron density observed by DEMETER satellite exhibits the pattern of wave number 4 around the magnetic equator. The longitudinal distribution of the electron density depends on the various tides and waves propagating from the lower atmosphere (Immel et al., 2006; Lühr et al., 2012; Xiong and Lühr, 2013). Although the solar activities are almost same during the observation period of CSES and DEMETER satellite, the different structures of the longitudinal distribution mean that the differences of lower atmosphere exist in the different solar cycles. The electron density enhancements at mid-latitude were detected for CSES, as well as the observation of DEMETER satellite, the outputs of IRI model in this study and other reported researches (e.g., Chen et al., 2012; Luan, et al., 2008; Xiong et al., 2019). Furthermore, we found that the phenomenon of electron density enhancements at mid-latitude for CSES is more obvious than that for DEMETER satellite in the nighttime, especially in 2019 (Figure 3). Zhong et al. (2019) emphasized that the phenomenon of electron density enhancements at mid-latitude for DEMETER satellite is more obvious than that for CSES, especially in 2019. The local time at night side of CSES is just right during this period, while the ascending node of DEMETER satellite is 22:30 LT, a little earlier than the main time range. The WSA is a prominent characteristic of Southern Hemisphere in the local summer, presenting close association with other essential features of the ionosphere (He et al., 2009; Horvath & Lovell, 2009). The synchronous variations of WSA make the correlation coefficients of electron density between CSES and other observations/models better in the Southern Hemisphere. In the daytime, the $Ne$ correlation coefficients between CSES and IRI model are

![Figure 17. The correlation coefficients between CSES and Swarm satellites along the latitudes by 1° interval. The red, blue and black lines represent Swarm A, B and C satellites, respectively. CSES, China Seismo-Electromagnetic Satellite.](image)

![Figure 18. The $Ne$ ratios between Swarm constellation and CSES. Left, middle and right panels are for Swarm A, B and C, respectively. CSES, China Seismo-Electromagnetic Satellite.](image)
low around the magnetic equator, showing in the right panel of Figure 13. From the Figures 10 and 11, it can be seen that the Ne data of IRI model at dayside have two crests in the EIA region, while in the topside of ionosphere, the Ne usually exhibits single peak around the magnetic equator (Zhang et al., 2014), such as the Ne variation shown in the left panel of Figure 15. Indeed, the discrepancy between in situ Ne of satellites and predictions of IRI model has been reported in some researches (Biliza et al., 2007; Lomidze et al., 2017; Lühr & Xiong, 2010). Zhang et al. (2014) also detected that the distribution of topside electron density observed by DEMETER satellite just shows a single crest over the equatorial area, which is different from the outputs of IRI 2007. Yan et al. (2020) found a single crest feature in electron density of CSES at the dayside. In a geomagnetically quiet day (November 3, 2018), the Ne variations along latitudes at the dayside were plotted in Figure 20. Left panel exhibits the satellite orbits, and the right panel gives the Ne distribution with the latitude, different colors representing different satellite orbits labeled at the northeast of the picture.

Figure 19. Multiple parameters observed by CSES for an ascending orbit (003116) on August 26, 2018. The panels from top to bottom represent orbit position, VLF electric field spectrum, electron density, electron temperature, ion density and ion temperature. CSES, China seismo-electromagnetic satellite; VLF, very low frequency.
No matter the location of the satellite track is, the electron density mostly exhibits single peak around the equatorial area. Therefore, we considered that the different patterns of electron density between the CSES and IRI model in the daytime have a strong connection with the low correlation coefficients around the magnetic equator.

The Ne patterns of CSES are consistent with observations of DEMETER satellite, Swarm constellation and the predictions of IRI model, while there are systematic biases in the values between different observations. First, although the altitude of DEMETER satellite is higher than that of CSES, the Ne values are almost same for the two satellites (Figures 6a and 6b), especially in the nighttime. A polynomial fit of degree 4 is applied to obtain the curve of the electron saturation region for DEMETER satellite according to the I-V curve (Lebreton et al., 2006). Based on the Orbit Motion Limited (OML) theory of collecting current for spherical probe (Mott-Smith & Langmuir, 1926), the Equation 5 with optimized parameters $a$, $b$, $c$ is applied to fit the curve of electron saturation region for CSES (Guan et al., 2012; Karamcheti & Steinbrüchel, 1999).

$$I_e = I_{e0}a \left(1 + \frac{e(V - b)}{kT_e}\right)^c$$

$I_e$ is electron current and $I_{e0}$ represents electron current at the potential voltage ($V_p$). $V$ is the voltage. $T_e$ means the electron temperature, which is determined from the slope of retardation region in the I-V curve. $k$ is the Boltzman constant, with the value of $1.38 \times 10^{-23}$; $e$ is the coulomb charge, with the value of $1.6 \times 10^{-19}$. The coefficients $a$, $b$, $c$ can be obtained by least square fitting in the electron saturation region. Taking the nighttime data of orbit 3113 (on August 26, 2018) as an example, the I-V curves of two fitting methods are shown in Figure 21. It can be seen that the Ne value ($2.466 \times 10^{10}$ m$^{-3}$) obtained by 4° polynomial fitting method is higher than the datum ($1.043 \times 10^{10}$ m$^{-3}$) obtained by parameterized OML fitting method. Therefore, we considered that the different fitting methods bring the discrepancy of Ne value between CSES and DEMETER satellite. Second, the Ne predictions of IRI model are higher than the Ne observations of CSES with 1–2 times in the nighttime and more 2 times in the daytime. The overestimating phenomenon of IRI model is not only detected by us but also by other researchers. Kakinami et al. (2013) found that the Ne values of DEMETER satellite are about 70% lower than those of IRI in the daytime data.
Lomidze et al. (2017) reported that a striking discrepancy between the Ne of Swarm and IRI can be seen over the equator during the morning overshoot, although the Ne data were adjusted by ISRs. Comparing the Ne data between IRI model and CHAMP, GRACE satellites, Lühr and Xiong (2010) showed that the equatorial ion fountain effect is strongly overestimated by IRI 2007 during the solar minimum, with 50% and 60% higher values for 2008 and 2009, respectively. Furthermore, the altitudes of CSES and Swarm B satellite are almost same, while 3–6 times systematic biases are still existing between the two datasets. The Langmuir probe for Swarm constellation is screwed on the satellite’s body with 8 cm long post (Knudsen et al., 2017), and the length of the sensor extension bar for CSES is 50 cm. As the shorter distance from the satellite surface, the Langmuir probe of Swarm constellation may be more easily interfered by the satellite. Although the altitudes of the two satellites are similar, the different distances of the sensors from the satellites’ bodies

**Figure 21.** I–V curves for the nighttime data of orbit 3113 (on August 26, 2018). The top and bottom panels are for the fitting methods of DEMETER satellite and CSES, respectively. The blue asterisks represent raw data. Yellow and black lines are the fitting curves for ion and electron saturation regions. Green dotted line is the slope of retardation region. The red line represents electron current which is the difference between total and ion current. The black circle denotes the potential voltage ($V_p$). The fitting methods in the electron saturation region (showing by black lines) are different for the two panels, 4-degree polynomial fitting method for DEMETER satellite and parameterized OML fitting method for CSES. CSES, China seismo-electromagnetic satellite; OML, orbit motion limited.
can also bring the discrepancies in the values. In a word, both hardware design and data processing may potentially have effects on the Ne systematic biases between the CSES and other observations.

5. Conclusions

Through the comparative analysis of electron density between CSES and other observations or models during one and half years, the results were concluded as the following.

(1) The Ne patterns for CSES are similar with those for DEMETER satellite during the same solar cycle, the maxima and minima nearly locating the same place. The correlation coefficients between the two data are higher in the Southern Hemisphere, especially in the region of Weddell Sea Anomaly.

(2) The observation data of CSES are almost consistent with the outputs of IRI 2016 empirical model, especially in the local summer hemisphere. The correlation coefficients between the two data have high values in the southern Atlantic Ocean region during the nighttime and daytime, almost exceeding 0.5. Furthermore, the correlation between CSES and IRI model is also better around the EIA crests during the daytime, while the coefficients are low at the magnetic equator. The Ne data of IRI model are almost 1–2 times higher than those of CSES during the nighttime. All of the ratios between model outputs and observation data are over 3 times during the daytime, and more than 10 times in the locations of Northern Hemisphere and southern Pacific Ocean.

(3) The variations of electron density along latitudes are almost same for the nearby orbits between CSES and Swarm constellation, even having similar subtle changes. As all of the correlation coefficients exceed 0.75, the two data are strongly correlated, especially for Swarm B satellite, the nearest one to the CSES altitude. The Ne values of CSES are lower 3–6 times than those of Swarm constellation.

In conclusion, although there are systematic biases in the values between the Ne data of CSES and other observations/models, the variation tendency of electron density can exhibit the ionospheric characteristics at the altitude of 507 km, with the ionospheric phenomena of wave number 3/4, electron density enhancements at mid-latitude, and WSA. The data of electron density can be applied to the ionospheric study, such as ionospheric climatology, ionospheric disturbances, and layer coupling. Furthermore, the comparisons between CSES and other observations/model can help to improve the quality and accuracy of the electron density.

Data Availability Statement

The authors acknowledge CSES mission, DEMETER mission, Swarm mission and IRI website for providing the electron density data. The websites for downloading these data are as follows: CSES data http://www.leos.ac.cn/, Swarm data http://earth.esa.int/Swarm, and IRI outputs https://ccmc.gsfc.nasa.gov/modelweb/models/iri2016_vitmo.php. DEMETER data have been acquired in the collaboration with the DEMETER satellite center (mparrot@cnrs-orleans.fr). F10.7 index were downloaded from the ftp (ftp://ftp.ngdc.noaa.gov/STP/space-weather/solar-data/solar-features/solar-radio/noontimeflux/penticton/penticton_adjusted/listings/listing_drao_noontimeflux-adjusted_daily.txt) and the website (https://www.spaceweather.gc.ca/solarflux/ssx-5-flux-en.php).

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