The first joint experimental results between SURA and CSES

XueMin Zhang1*, Vladimir Frolov2,4, ShuFan Zhao1, Chen Zhou3, YaLu Wang1, Alexander Ryabov2,4, and DuLin Zhai1

1Institute of Earthquake Forecasting, China Earthquake Administration, Beijing 100036, China; 2Radiophysical Research Institute, Nizhny Novgorod 603950, Russia; 3Department of Space Physics, School of Electronic Information, Wuhan University, Wuhan 430072, China; 4Kazan Federal University, Kazan 420008, Russia

Abstract: In June 2018, for the first time, the SURA heating facility in Russia, together with the in-orbit China Seismo-Electromagnetic Satellite (CSES), carried out a series of experiments in emitting high frequency (HF) O-mode radio waves to disturb the ionosphere. This paper reports data from those experiments, collected onboard CSES, including electric field, in-situ plasma parameters, and energetic particle flux. Five cases are analyzed, two cases in local daytime and three in local nighttime. We find that the pumping wave frequencies $f_0$ in local daytime were close to the critical frequency of the $F_2$ layer $f_0 F_2$, but no pumping waves were detected by the electric field detector (EFD) on CSES even when the emitted power reached 90 MW, and no obvious plasma disturbances were observed from CSES in those two daytime cases. But on June 16, there existed a spread F phenomena when $f_0$ was lower than $f_0 F_2$ at that local daytime period. During the three cases in local nighttime, the pumping waves were clearly distinguished in the HF-band electric field at the emitted frequency with the emitted power only 30 MW; the power spectrum density of the electric field was larger by an order of magnitude than the normal background, with the propagating radius exceeding 200 km. Due to the small $f_0 F_2$ over SURA in June at that local nighttime period, $f_0$ in these three cases were significantly higher than $f_0 F_2$, all belonging to under-dense heating conditions. As for the plasma parameters, only an increase of about 100 K in ion temperature was observed on June 12; in the other two cases (with one orbit without plasma data on June 17), no obvious plasma disturbances were found. This first joint SURA-CSES experiment illustrates that the present orbit of CSES can cross quite close to the SURA facility, which can insures an effective heating time from SURA so that CSES can observe the perturbations at the topside ionosphere excited by SURA in the near region. The detection of plasma disturbances on June 12 with under-dense heating mode in local nighttime provides evidence for likely success of future related experiments between CSES and SURA, or with other HF facilities.

Keywords: CSES satellite; SURA; ionospheric perturbations; electric field; HF pumping wave

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1. Introduction

Ionospheric high frequency (HF) heating facilities have been used since the last century to disturb the ionosphere, or carry the ELF/VLF (Extremely Low Frequency/Very Low Frequency) electromagnetic signals into the topside ionosphere. When satellites crossed over these facilities, many interesting phenomena have been observed. The electron temperature enhancements caused by powerful incoherent scatter radars have been reported many times, such as the observations at Arecibo (Gordon et al., 1971; Mantas et al., 1981), and at EISCAT (European Incoherent Scatter) (Rietveld et al., 2003; Liu MR et al., 2017). Piddyachiyi et al. (2008) reported DEMETER (Detection of Electro-Magnetic Emissions Transmitted from Earthquake Regions) satellite observations of ELF/VLF radiations in a quite large lateral distance generated by the HAARP facility (High Frequency Active Auroral research Program). Milikh et al. (2008) presented the first experimental evidence of plasma modifications on DEMETER induced by HAARP heater, in which the ion temperature increased 60%–70%, 200%, and 30% respectively in three cases at over-dense heating condition. Vartanyan et al. (2012) further reported the plasma density ducts caused by HAARP wave injections, which were detected both by DEMETER and DMSP (Defence Meteorological Satellite Program) satellites. Frolov et al. (2008b, 2016) reported detections from DEMETER and DMSP satellites of density ducts formed by the SURA heating facility, and summarized the conditions facilitating the ducts formation, including the experimental time, pumping wave frequency, emitted power, magnetic-zenith effect, and so on. Zhang XB et al. (2016) summarized three typical heating events between SURA-DEMETER, and reported that $T_i$ increased about 100 K in two cases with one $f_0$ being equal to $f_0 F_2$ and another $f_0$ less than $f_0 F_2$. Kuznetsov and Ruzhin (2014) presented two experiments from the SURA HF facility in local nighttime, on Oct. 2 2007 and Oct. 25 2010, which triggered $F_2$-spread with under-dense conditions. Cohen and Golkowski (2013) reported their experiments with HAARP to test the effective generation
mode for 500–3500 Hz magnetic fields.

Thus satellite detection has been shown to be effective in measuring the generation mechanism of plasma ducts and ELF/VLF emissions induced by HF heaters. Further experiments can provide useful information for assessing the observing accuracy and resolution of satellite detection of small scale plasma irregularities during the heating period. In this paper, the first experimental results are exhibited between the China Seismo-Electromagnetic Satellite and the SURA heating facility in Russia, and some preliminary results are discussed.

2. Basic Information

2.1 CSES Satellite

The China Seismo-Electromagnetic Satellite (CSES, also named as ZH-1) was launched successfully on Feb. 2 2018. It is the first geophysical field measurement satellite and space-based platform for earthquake research in China (Shen XH et al., 2017). There are eight scientific payloads onboard, including an electric field detector (EFD) to detect the three-component electric field (Chen T et al., 2018); a search-coil magnetometer (SCM) to observe the magnetic field (Cao JB et al., 2018); a high precision magnetometer (HPM) to obtain the three components of the magnetic field (Cheng BJ et al., 2018); a Langmuir probe (LAP) for electron density and temperature; a plasma analysis package (PAP) for ion density, composition, temperature and drift velocity; a tri-band beacon (TBB) for emitting three frequency waves to the receivers built on the ground; a GNSS occultation receiver (GOR) for total electron content (TEC) and electron density profile (Lin J et al., 2018); and a high energy particle detector (HEPD) for energetic electrons and protons (Ambrosi et al., 2018). CSES is a sun-synchronous orbit satellite at altitude of 507 km, with inclination of 97.4°, and revisited period of 5 days (Shen XH et al., 2018). Its ascending and descending nodes are 14:00 LT and 2:00 LT. In this paper, data analyzed are mainly from EFD, LAP and PAP. There are four bands in EFD, with the sampling rate in ULF of 125 Hz, in ELF of 5 kHz, in VLF of 50 kHz, and in HF of 10 MHz. The spectrum data calculated onboard the satellite in the VLF and HF bands were averaged along the whole orbit; very short time waveforms were stored at the beginning of each observing point, for example with 0.2048 ms waveform data in the HF band, so the waveforms in HF band were discontinuous. During the experimental period, the BURST mode was on, with sampling rates of 1.5 s for LAP and 0.5 s for PAP.

There are four booms used in electric field detection, displayed in Figure 1. Their exact positions are listed in Table 1 under satellite coordinates, in which X is the satellite flying direction, Z points to the Earth, and Y coincides the right-handed coordinate of Z-X. A

![Figure 1. The spatial position of the four booms (a–d) in electric field detection onboard CSES (X, Y and Z represent the satellite direction, in which X is the satellite flying direction, Z points to the Earth, and Y coincides the right-handed coordinate of Z-X).](image)

Table 1. The position of four booms at satellite coordinate (Unit: mm)

| Sensor | X     | Y     | Z     |
|--------|-------|-------|-------|
| a      | 25.75 | −2821.22 | 4822.19 | 1429.2 |
| b      | −4944.75 | 70 | 514 | 4291.46 |
| c      | 518 | −4040.99 | −3599.82 | 3119.07 |
| d      |       |       |       |

2.2 SURA HF Heating Facility

The SURA facility is located about 120 km east of Nizhny Novgorod, at 56.15°N, 46.1°E. It has been operated for more than 30 years (since 1981). The facility consists of three units, which includes a short wave transmitter to generate high frequency signals with maximal output power of 250 kW; each transmitter is connected with a sub-antenna array, which consists of 4 by 12 wideband dipoles. Each unit can be operated independently, and also can be combined in pairs and in three, to radiate ordinary wave (O mode) and extraordinary wave (X mode) within a frequency band of 4.3–9.5 MHz. When all three units of the facility are operated in coherent mode, the effective radiated power (ERP) of the pumping wave (PW) is of about 80 MWs at \( f_0 = 4300 \) kHz, increasing up to of 260 MWs at \( f_0 = 9500 \) kHz. The antenna beam can be scanned in the geomagnetic field plane between 45° to the north and 45° to the south from the vertical direction. In general, it always inclines 12° to the south to make the emitted waves propagate along the geomagnetic field lines at the altitude of the upper hybrid resonance of PW–plasma interactions and thus disturb the ionosphere more strongly due to the magnetic zenith effect (Gurevich, 2007; Frolov et al., 2007).

3. Results of SURA-CSES Experiments

Table 2 shows the first joint experiments between SURA and CSES in June 2018, according to the predicted orbits when CSES crossed the HF-disturbed magnetic field flux tube over the SURA facility within a radius of 50 km from the tube center. The time \( T' \) in Table 2 is the time of the closest position of the satellite to the
center of the tube. Two experiments took place in local daytime, and three in local nighttime. Note that all PWs were radiated in O mode during these séances. The local nighttime experiments, which were aimed at measurements of the SURA antenna pattern, were carried out on June 7, 12, and 17, respectively, all with frequency of 4.785 MHz, and intermittent radiating mode (900 ms–on, 100 ms–off) to mark the SURA radiation. In the two local daytime experiments on June 11 and 16, which were aimed at measurements of features of HF-induced plasma disturbances, the continuous wave mode (CW) was used, with different emitted frequencies.

### 3.1 Daytime Experiments

It is well known that powerful HF radio waves can disturb the ionosphere and form artificial ducts at outer ionosphere altitudes. By taking into account the payloads on CSES, three of them are selected out: the pumping waves from EFQ, and plasma parameters from LAP and PAP. Figure 2 presents all the records along orbits #1965 and #2041 on June 11 and 16 from north to south. From top to the bottom, they are the orbit position (red line: orbit; blue star: SURA facility), spectrum of $E_{\text{ad}}$, in electric field in HF band, electron density ($N_e$), electron temperature ($T_e$), and ion temperature ($T_i$).

As for the orbit #1965-0 (-0 means the down-orbit in local daytime) on June 11, the orbit was very close to SURA, but a little to the west as shown in Figure 2A. The emitted frequency was 4.3 MHz as listed in Table 2. In the second panel of Figure 2, no obvious wave signals occurred at 4.3 MHz over the SURA latitude and its neighboring region, which illustrates that this pumping HF wave is difficult to penetrate directly into the ionosphere with large plasma content in local daytime. Also there were no apparent variations in plasma parameters of $T_e$, $N_e$, and $T_i$. Although $N_e$ modulated over this region, it varied very smoothly, and it is hard to be correlated with the HF radio waves without detection of the emitted signals.

We checked all the parameters along orbit #2041-0 on June 16 in Figure 2B, revisiting the position of #1965-0 after 5 days. Although some strong signals around 4.68 and 4.97 MHz were detected, they continued and covered the whole region, showing no close relationship with SURA in space position. There was no pumping HF wave signals enhancement at 4.785 MHz in $E_{\text{ad}}$ spectrum. Significant increasing perturbations were detected in $T_e$, but they occurred at the south and north sides, not just over SURA. $N_e$ modulated over this region just as those along #1965-0.

From the two SURA-CSES local daytime cases it was found that HF radio waves were hard to penetrate directly into the ionosphere to the satellite altitude. Previous studies about tens of cases of observations from DEMETER and DMSP satellites (Frolov et al., 2008b) also report that daytime waves and corresponding perturbations excited by SURA were not observed, verifying the quite weak variations in local daytime. Vartanyan et al. (2012) proved with the SAMI2 model that due to the strong absorption of electromagnetic waves when they penetrate into the ionosphere, the daytime power and width at the pumping wave frequency will be smaller and narrower than in nighttime. In our cases, the pumping wave frequency was 4.3 MHz while the critical frequency of the $F_2$ layer, $f_0F_2$, was 4.1 MHz and the $f_0Es$ was up to 4.0 MHz on June 11 as listed in Table 1, where they were close to each other. In this case, the pumping waves had a chance to penetrate into the ionosphere to the satellite height. On June 16, the pumping wave frequency was 4.785 MHz while $f_0F_2$ was about 5.0 MHz and an artificial F spread was found at 4.8 MHz. So for the latter case, the emitted wave frequency was lower than $f_0F_2$ over SURA, which illustrates the strong attenuation in lower ionosphere for the pumping waves into the topside ionosphere. But the emitted power reached 90 MW on that day, and HF waves may interact with the lower ionosphere and help to form the artificial F spread.

### 3.2 Nighttime Experiments

Because the orbit of CSES is strictly revisited each 5 days, the previous revisited orbit #1834 on June 2 passing by SURA before the experiments was selected and shown in Figure 3A, with the experimental case along #1910-1 (-1 means the up-orbit in local nighttime) on June 7 in Figure 3B with the same parameters in Figure 2. The orbit position in Figure 3 shows that these revisited orbits were just over SURA from south to north. Comparison of data from the two orbits reveals that during the SURA-CSES experiment on June 7 the pumping waves at 4.785 MHz were quite clear along #1910-1 orbit over SURA around latitude 56.15°N and longitude 46.1°E, with the $E_{\text{ad}}$ spectrum larger than 0.1 $\mu$V m$^{-2}$ Hz$^{-1}$. When there was no experiment along #1834-1 on June 2 (Figure

### Table 2. Information for the SURA-CSES experiments

| Date (yyyy-mm-dd) | UT (hh:mm) | $f_0$ (MHz) | Working Mode | Emitted ERP (MWs) | $f_0F_2$ (MHz) |
|-------------------|------------|-------------|--------------|------------------|----------------|
| 2018-06-07        | 22:12–22:22 22:17 | 4.785 | 900 ms–on, 100 ms–off | 30 | 2.9 |
| 2018-06-11        | 11:35–11:55 11:50 | 4.3 | CW | 60 | 4.1 (Es up to 4.0) |
| 2018-06-12        | 22:11–22:21 22:16 | 4.785 | 900 ms–on, 100 ms–off | 30 | 3.9–3.5 |
| 2018-06-16        | 11:35–11:55 11:50 | 4.785 | CW | 90 | 5.0 → 4.8 (there is an artificial F, spread) |
| 2018-06-17        | 22:11–22:21 22:16 | 4.785 | 900 ms–on, 100 ms–off | 30 | 3.6 |

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however, the signals around 4.785 MHz were about 0.01 μV m⁻² Hz⁻¹, similar to background signals. So it can be confirmed that CSES observed the pumping waves from SURA, with the power spectrum density increasing by an order of magnitude. Along #1910-1 orbit, the propagating distance of pumping waves was more than 500 km. As for the four in-situ plasma parameters, no obvious disturbances were detected at the same time and same region in this case. On June 7, fF₂ was 2.6 MHz, so the emitted wave frequency 4.785 MHz was much higher, which illustrates the under-dense heating condition in this case and may explain why no plasma irregularities were formed.

CSES data were also collected during two nighttime experiments,

![Figure 2A](image-url)

**Figure 2A.** Multi parameters along the orbits of 1965-0 on June 11 (from top to bottom, six panels are in the order: the orbit position, HF electric field spectrum, Nₑ, Tₑ, Nᵢ, and Tᵢ).
but without LAP data on June 12 and without LAP and PAP data on June 17. The same parameters as in Figure 3 were plotted in Figure 4 along #1986-1 on June 12. It can be seen that the pumping waves at 4.785 MHz were also quite clear in $E_{ad}$, whereas in PAP observations, $T_i$ at the bottom of Figure 4 showed some increasing variations to 100 K, but ion density ($N_i$) presented no obvious disturbances. As listed in Table 2, $f_0F_2$ on June 12 was 3.9 MHz over the experimental time period, smaller than $f_0=4.785$ MHz. Unfortunately, there were no records in LAP over this region, and the variations only in $T_i$ could not verify the formation of density ducts during this case. The clear electric field signals at pumping waves along #1910-1 and #1986-1 all demonstrated that they could easily penetrate into the topside ionosphere in local nighttime with $f_0$ higher than $f_0F_2$, even with the emitted power.
Onboard CSES, a particle detector is able to record lower and higher energetic electrons and protons. Figure 5 shows the electron flux along the orbit #1986-1 on June 12; from top to bottom are orbit position, counting rate of electrons, electron flux at lower energy band under 2 MeV, and electron flux at different pitch angles. It can be seen that SURA was close to the Van Allen radiation belt at high latitudes, and there did not occur significant particle precipitation or pitch angle diffusion during the experimental time period over SURA.

To understand further the propagation features in HF pumping waves, along the orbit #2062_1 on June 17, the spectrum at 4.785 MHz was selected in three channels of electric field. As shown in Figure 6, the electric field in \( E_{ab} \), \( E_{cd} \), and \( E_{ad} \) reached maximal val-

**Figure 3A.** Multi parameters detected by CSES along the orbits of 1834-1 on June 2 without experiment during experiment (same parameters as listed in Figure 2).
values of $10^{-0.5}$, $10^{-2}$, $10^{-0.5}$ $\mu$V$^2$m$^{-2}$Hz$^{-1}$, respectively, at the latitude approximately $56^\circ$ (Figure 6b, 6d, 6f), indicating detection of the direct pumping waves from SURA. And also, the latitudinal propagation scale with $\pm2^\circ$ in three channels was exhibited. Comparing the three channels, $E_{cd}$ detected the smallest electric field (Figure 6c, 6d), almost two orders of magnitude lower than the others. In Figure 6c, there were many vertical lines in the picture, illustrating strong background noise in this direction, almost similar in amplitude to the pumping waves. According to the direction of the four sensors, $E_{ad}$ was nearly parallel to the $Y$ direction of the satellite, vertical to the $X-Z$ plane, almost horizontal in the east-west direction, while $E_{cd}$ was with a big weight in the vertical $Z$ direction. In all these experiments, the HF waves were emitted by O-mode with right-rotated circular polarization, which means a bigger components in two horizontal directions of $X$ and $Y$ given the satellite coordinates. The electric field detection in the three channels on CSES was thus consistent with wave propagation theory, which predicts the highest electric field in horizontal components.

Figure 3B. Multi parameters detected by CSES along the orbits of 1910-1 on June 7 during experiment (same parameters as listed in Figure 2).
4. Discussion and Conclusion
Analysis in this text demonstrates that the satellite observations of pumping waves exhibited big differences between the daytime and nighttime experiments. CSES observations detected no pumping waves at the emitted frequency from SURA in the HF-band electric field in local daytime, even though $f_0$ was a little higher than $f_0F_2$ on June 11, and the emitted power reached 90 MW on June 16. It should be noted that the HF-band electric field on CSES has strong noise background about 1 $\mu V^2 m^{-2} Hz^{-1}$, while many strong signals at certain frequencies have been detected always with clear and continuous lines in the spectrum picture, such as at 4.4, 4.68, 4.97 MHz, etc. This background may further reduce the possibility for detecting the pumping waves with small amplitude after they penetrate into the ionosphere in local daytime. In local nighttime, with the emitted power of only 30 MW, three or-

![Image of Figure 4: Three channels of electric field along orbits 1986-1 on June 12 (same parameters as listed in Figure 2).](image-url)

**Figure 4.** Three channels of electric field along orbits 1986-1 on June 12 (same parameters as listed in Figure 2).
bits all observed the pumping waves at 4.785 MHz in three channels during three experiments, with the probability of 100%. And the propagation distance of pumping waves in the electric field exceeded 200 km along the orbit from south to north, with the maximum values occurring at 56° latitude just over SURA. The typical artificial ducts were apparently not constructed at this time.

**Figure 5.** The electron flux along 1986-1 orbit on June 12 (the panels from top to bottom are: orbit position, counting rate of 9 tubes, electron flux with energy, and electron flux with pitch angle).

**Figure 6.** The three channels in electric field (a: $E_{ab}$; c: $E_{cd}$; e: $E_{ad}$) and their spectrum at 4.785 MHz (b: $E_{ab}$; d: $E_{cd}$; f: $E_{ad}$) along the orbit 2062-1 on June 17.

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period; no simultaneous perturbations were detected in in-situ plasma parameters and energetic particle flux. Previous experiments between SURA and satellites DEMETER and DMSP (Frolov et al., 2008a, b) identified conditions for formation of ducts, including the time in the morning or evening, high emitted power (larger than 40 MW), distance from the satellite to the disturbed magnetic flux tube limited to less than 50 km, and so on. Vartanyan et al. (2012) also thought that the artificial ducts were produced most efficiently when the heating frequencies were quite close to the critical frequency $f_i f_2$ based on the experiments between HAARP and DEMETER and DMSP spacecrafts. So in these first cases between SURA-CSES, the early morning time and distance coincided with the identified requirements, but the emitted power was low, and the HF wave $f_i$ was much larger than $f_i f_2$, which may explain why density ducts did not occur over SURA at the CSES satellite altitude during this time period. But on June 12, the increasing $T_i$ illustrated possible interaction between HF waves and plasma in the $F_2$ layer.

This is the first time that joint experiments have been carried out between CSES and a HF facility. CSES is a polar-orbit satellite, with revisited orbit of 5 days (Shen XH et al., 2018). Normally it can observe about 15 orbits in one day crossing the whole world, so the closest distance between two orbits in 5 days is about 500 km. But the HF heater has strict conditions in order to disturb the ionosphere, especially its distance limitation. Results of the five experiments in June 2018 illustrate that in one month there will be 10–12 orbits of the CSES that will put it above the SURA facility within a distance of 100 km, half in daytime and half in night. Successful detection of pumping waves in electric field in nighttime experiments demonstrates that the basic conditions for joint experiments between SURA and CSES have been satisfied. Due to lower emitted power, and higher pumping wave frequencies relative to $f_i f_2$, artificial plasma ducts or particle precipitation induced by SURA were not clearly confirmed at this time, given the mostly under-dense heating condition that prevailed during these experiments. In addition, strong background noise background in the HF-band electric field on CSES also raises new questions regarding how to improve the processing method or detecting technology to get better quality data in future experiments.

Until now, scientists have not totally understand the heating mechanism, and new kinds of perturbations in plasma parameters and electromagnetic field excited by powerful HF waves have been found continuously by experiments using advanced technologies, especially together with satellite observations. The results on June 12 give additional confidence that future experiments will provide useful new information. New emitted modes are expected to be arranged and complemented in the future between CSES and SURA or other HF facilities under suitable conditions.

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