



Multi-Station and Multi-Instrument Observations of F-Region Irregularities in the Taiwan–Philippines Sector

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Abstract: In this study, a multi-station and multi-instrument system, organized and proposed for ionospheric scintillation and equatorial spread-F (ESF) specification and their associated motions in the Taiwan–Philippines sector, is outlined. The issues related to the scintillation and ESF event observed on 26 October 2021, at magnetic quiet conditions are presented and discussed. We first indicate the existence of a plasma bubble in the Taiwan–Philippines sector by using the FormoSat-7/Constellation Observing System for Meteorology, Ionosphere, and Climate-2 (FS7/COSMIC2) GPS/GLONASS radio occultation observations. We verify the latitudinal extent of the tracked plasma bubble using the recorded ionograms from the Vertical Incidence Pulsed Ionospheric Radar located at Hualien, Taiwan. We further discuss the spatial and temporal variabilities of two-dimensional vertical scintillation index $V S_4$ maps based on the simultaneous GPS L1-band signal measurements from 133 ground-based receivers located in Taiwan and the surrounding islands. We also operate two high-sampling, software-defined GPS receivers and characterize the targeted plasma irregularities by carrying out spectrum analyses of the received signal. As a result, the derived plasma irregularities moved eastward and northward. Furthermore, the smaller the irregularity scale, the higher the spectral index and the stronger the scintillation intensity were at lower latitudes on the aimed irregularity feature.

Keywords: equatorial and low-latitude ionosphere; ionospheric irregularity; scintillation; radio occultation observation; COSMIC; ionogram; GPS/GNSS



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1. Introduction

Ionospheric scintillation has significant impacts on space-based radio communication, wave propagation, and navigation system performance. The main effects of scintillation on the transionospheric radio system are signal loss and/or phase cycle slips, which cause difficulties in regard to locking the receiver signal. There is no doubt that satellite radio signal scintillation is a consequence of a scattering mechanism, as radio waves are propagating through random electron density (N_e) fluctuations, especially within the F-region ionosphere, where the irregularity layer is sufficiently thick. Many excellent ionospheric scintillation theory and observation reviews have been published [1–4]. Comprehensive studies on the physics and theories of ionospheric irregularities and scintillations can also be found in books by [5,6].

The effects of ionospheric scintillation are most intense in the equatorial region, moderate at high latitudes, and minimum at middle latitudes [7]. At equatorial latitudes and the time near and/or soon after sunset, the zonal neutral wind and conductivity gradient caused by the sunset terminator interact develop an enhanced eastward electric field, called

pre-reversal enhancement (PRE), generally at F-region heights [5,8,9]. As a result, the ionosphere moves upward, develops steep density gradients and large-scale plasma depletions in the bottom side F-region, and becomes unstable, triggering the Rayleigh–Taylor (R–T) instability. The plasma depletions, called plasma bubbles, become populated with mesoscale or small-scale irregularities and rise to great heights. These plasma bubbles, extended in altitude, also map out along magnetic field lines to the north and south of the magnetic equator, i.e., higher magnetic latitudes. These structured irregularities generally move eastward by the action of a vertical oriented polarization electric field. Undergoing a non-linear cascade process of electric field driving and wave-wave coupling [10], irregular structures drift and vary from large- to small-scale. The spectral distribution of irregularities includes a broad component associated with waves. Equatorial spread-F (ESF) thus stems from high-frequency radar observations of the “spread” of the ionospheric echoes in ionograms and can be used to describe equatorial and low-latitude F-region instability phenomena. Scintillation and ESF activities attain a maximum value during high sunspot activity periods, especially during equinoxes (March, April, September, and October), owing to the increased value of the background ionization density [11]. In particular, low-latitude scintillation can be dictated by solar transients, such as magnetic storms [11].

Several techniques have been used to observe and study ionospheric irregularities and scintillations. These include sounder, radar backscatter, in-situ measurements on-board rockets or satellites, ground-based satellite beacon signal observations, space-based navigation beacon observations using radio occultation (RO) techniques, etc. Earlier investigations [12] developed an operational system, named the SCIntillation Network Decision Aid (SCINDA), to nowcast and forecast scintillation. At the operator terminal, the SCINDA data were combined with an empirical plasma bubble model to generate three-dimensional maps of irregularity structures and two-dimensional outage maps for the equatorial region in the American sector. In this study, another multi-station and multi-instrument system, developed for ionospheric scintillation and ESF specification in the Taiwan–Philippines sector, is outlined. The issues related to the scintillation and ESF event observed on 26 October 2021, are presented and discussed. We shall first indicate the existence of a plasma bubble in the Taiwan–Philippines sector using the FS7/COSMIC2 Global Positioning System (GPS) or GLObal NAVigation Satellite System (GLONASS) RO observations. We shall verify the latitudinal extent of the tracked plasma bubble using the recorded ionograms from the Vertical Incidence Pulsed Ionospheric Radar (VIPIR) located at Hualien (23.89°N, 121.55°E, dip latitude 17°N), Taiwan. We further discuss the spatial and temporal variabilities of two-dimensional scintillation index maps based on the simultaneous GPS L1-band signal measurements from 133 ground-based receivers located in Taiwan and the surrounding islands. We also operate two high-sampling, software-defined GPS receivers and characterize the targeted plasma irregularities by carrying out spectrum analyses of the received signal. Overall, we summarize the derived plasma irregularity and ESF characteristics and point out a potential precursor for post-sunset scintillation and ESF events.

2. System Description

Since June 2019, the Taiwanese American FS7/COSMIC2 program has been executing active limb sounding of the Earth’s neutral atmosphere and ionosphere via GPS/GLONASS RO observations from low-Earth orbiting (LEO) satellites. Similar to the prior mission, FS3/COSMIC, the FS7/COSMIC2 is a six-LEO-satellite constellation mission but orbits at 24° inclination and ~550 km altitudes (~720 km altitudes for parking orbits). It enhances the Global Navigation Satellite System (GNSS) receiver’s capability to receive multi-channel (1.5 GHz and 1.2 GHz) GPS and GLONASS satellite signals and can provide more than 5000 RO observations per day within the region between the geographic latitudes of $\pm 40^\circ$. Each RO observation can provide a set of limb-viewing measurements on GNSS signal intensity and phase from the LEO satellite altitude to the Earth’s surface. Those measurements can be further retrieved into N_e and limb-viewing scintillation index

S_4 profiles in altitudes [13,14]. In this study, we propose to identify a plasma bubble in the Taiwan–Philippines sector by using the FS7/COSMIC2 GPS/GLONASS RO observations. Meanwhile, the Taiwan–Philippines sector is defined as the ionospheric region located in $20^\circ \pm 15^\circ$ N and $120^\circ \pm 15^\circ$ E geographic coordinates, where the geomagnetic latitudes are from $\sim -3^\circ$ to 25° .

The Hualien VIPIR is a modern ionospheric radar (also termed ionospheric sounder or ionosonde) that fully digitizes complex signal records and uses multiple parallel receiver channels for simultaneous signal measurements from multiple spaced receiving antennas [15]. As a usual ionospheric sounder, the Hualien VIPIR transmits pulsed waveforms in the medium- and high-frequency (MF/HF) bands and measures the envelope group delays, i.e., virtual ranges, of ionospheric echoes to produce ionograms with ionospheric trace $h'(f)$ as a function of the radio carrier frequency. Details of the system can be found in [16].

Other sources of scintillation observations are the 133 ground-based GPS receivers located in Taiwan and the surrounding islands. They are operated and maintained by the Central Weather Bureau (CWB) of Taiwan and routinely provide 1-Hz satellite navigation system data (in the RINEX format). The online processing includes determinations of scintillation index S_4 and the two-dimensional vertical S_4 map in the Taiwan–Philippines sector. Based on earlier investigations [17], the theoretical and experimental analyses show that scintillation index S_4 values become underestimated when a sampling spatial scale is larger than the first Fresnel zone (FFZ). We note that the 1-Hz sampling rate from ground-based GPS receivers is high enough to determine complete S_4 values but not to characterize the signal scintillation spectrum. Thus, we have designed and implemented a software-defined receiver in order to acquire and track GPS (and Satellite-Based Augmentation System, SBAS) L1-band C/A code signals [18,19]. Compared with most commercial GPS receivers, software-defined GPS receivers offer added flexibility and versatility by implementing most functions in software. Another advantage of a software-defined GPS receiver is that it could have a maximum sampling rate of 1000 Hz due to the L1-band Coarse Acquisition (C/A) code duration of 1 millisecond, and the executing sampling rate can be much higher than that of a usual commercial GPS receiver. Spectrum analyses on the received signals of two software-defined GPS receivers located at Chungli (24.97° N, 121.19° E) and Hualien (23.89° N, 121.55° E), Taiwan will be used to characterize the targeted ionospheric irregularities.

3. Results

This section presents the multi-station and multi-instrument observations of a scintillation event that occurred in the Taiwan–Philippines sector on 26 October 2021, which was at magnetic quiet conditions, referring to K_p indexes between 0+ and 2+. Figure 1 shows the geographical geometry of the F-layer irregularity observations obtained during 13:00–15:30 UT, i.e., 21:00–23:30 LT in Taiwan, on 26 October 2021, by the FS7/COSMIC2 GPS/GLONASS RO sounding experiment. Six (#1 to #6 observations) out of fourteen RO observations were recorded and classified as scintillation observations according to their maximum limb-viewing L1-band S_4 values larger than 0.1 [14]. Their recording times, which are the FS7/COSMIC2 LEO satellite orbiting times at the peak altitudes of RO observations, are used to identify the scintillation event period, at least from 13:54 to 14:59 UT. For each RO scintillation observation, a set of RO limb-viewing links at a 15 s sampling rate (between 150 and 450 km altitudes), which connects the occultation points to their conjugate points, is shown in coded colors of L1-band S_4 values to present the possible projection area of ionospheric irregularities, and the trace of perigee points (or tangent points) is also shown. We note that the first three (#1, #2, and #3) RO observations are located near the magnetic equator and experience strong scintillations. The later three (#4, #5, and #6) RO observations are located in the northeast directions of the observations #1, #2, and #3 and could be their latitudinal mapping-out cases; thus, they experience weaker scintillations. In contrast, as shown in Figure 1, the peak tangent point positions of the other

eight RO observations without definable scintillations are located outside of the aimed scintillation area covering observations #1 to #6.

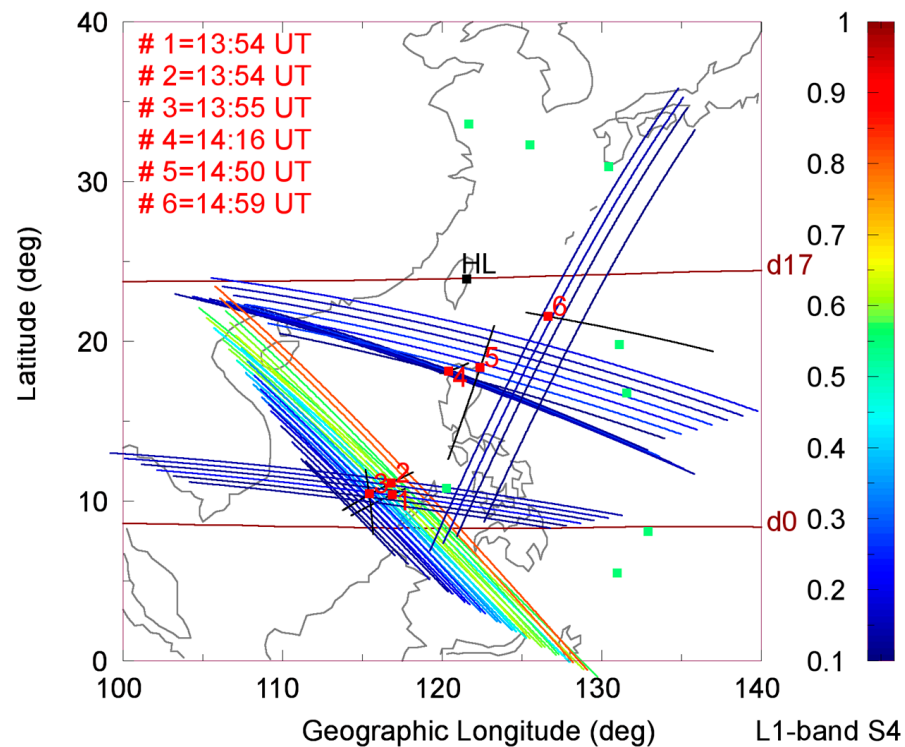


Figure 1. Geographical geometry of the F-layer irregularity observations during 13:00~15:30 UT on 26 October 2021, by the FS7/COSMIC2 GPS/GLONASS RO sounding experiment. Six out of fourteen RO observations were obtained and classified as the scintillation observations #1 to #6. Sets of limb-viewing links (at a de-sampling rate of 15 s and altitudes between 150 to 450 km) connecting the occultation points to their conjugate points are shown in coded colors by L1-band S_4 values to present the possible projection area of ionospheric irregularities. The traces of limb-viewing tangent points are also shown in black. The peak locations of the other eight RO observations without scintillation are shown by green squares, the location of the Hualien VIPIR position is shown by a black square, and two magnetic latitude lines at dip 0° and 17° are shown in brown.

Figure 2 shows the RO scintillation observations #1 and #4 with more information, including the limb-viewing L1-band signal-noise-ratio (SNR) amplitude profiles at both the occulting and calibrating sides, the resulting undersampling S_4 profiles, and the retrieved N_e profile. We note that the L2-band signals are much weaker and thus do not have enough sensitivity to derive reliable S_4 values to be shown in this paper. On the other hand, the derived S_4 values are from “undersampling” measurements because S_4 values become saturated and completed when a sampling spatial scale is less than the FFZ, but otherwise, S_4 values could be underestimated at undersampling conditions [17]. The FFZ is defined by $D_F = \sqrt{\lambda L}$, where λ is the radio wavelength and L is the distance from the irregularity position, which is assumed to be the tangent point position along a limb-viewing GPS/GLONASS-LEO ray, to an LEO satellite position in this study. For those tangent-point altitudes from 400 to 200 km, the FFZ scale sizes for the L1-band signals are between 516 and 643 m. Therefore, the Fresnel frequency can be obtained via $f_F = v/\sqrt{2} D_F$, where v is the relative radio-scanning speed to the ionosphere. The derived Fresnel frequency is thus approximately 2.1 (2.6) Hz at 400 (200) km altitude for a frozen ionosphere. We note that the upward drift velocity of plasma irregularities is usually less than 50 m/s [4], which is much lower than the vertical component (~ 2 km/s) of LEO satellite velocity at F-region altitudes and can be ignored to estimate the corresponding Fresnel frequency. We conclude that the sampling rate of FS7/COSMIC2 RO observations on the

ionosphere is 1 Hz and less than the possible Fresnel frequencies of plasma irregularities, and thus the derived S_4 values should be underestimated at undersampling conditions.

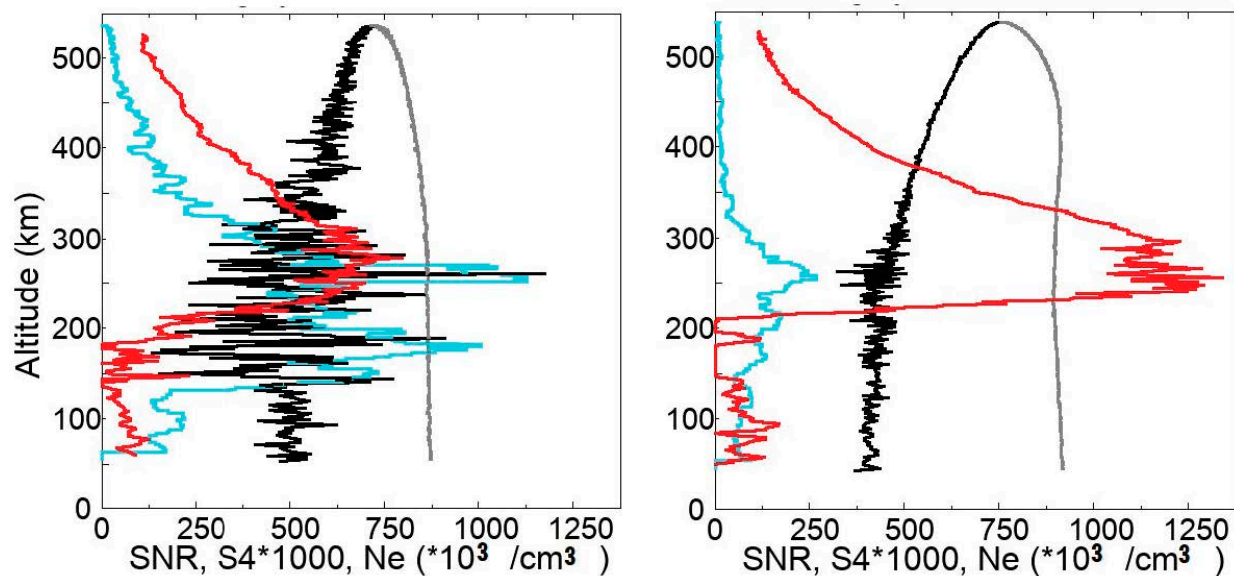


Figure 2. Results of FS7/COSMIC2 RO scintillation observations #1 (left panel) and #4 (right panel) as in Figure 1. Both figures show the limb-viewing L1-band SNR amplitude profiles at the occulting (calibrating) side in black (grey) and the resulting undersampling S_4 profiles in cyan. The retrieved N_e profiles are shown in red.

As shown in Figure 2, strong and moderate fluctuations occur in the L1-band SNR amplitudes of observations #1 and #4, respectively, from the occulting-side observations but not from the calibrating-side observations. It indicates that the amplitude fluctuations are induced by the ionospheric irregularities, which are located along the limb-viewing links between the occultation points and their conjugate points, as shown in Figure 1. We note that the strong amplitude fluctuations, i.e., large undersampling S_4 values, as well as the N_e fluctuations from observation #1, were distributed over a wider altitude region up to the LEO orbiting altitude than those from observation #4, and the peak scintillations and N_e irregularities happened around the F-layer electron density peaks. This is consistent with the observations from the theoretic descriptions in the Introduction section.

Equatorial spread-F (ESF) features usually accompany equatorial plasma bubbles and have been observed by numerous authors using ionosonde. In this study, we operated the Hualien VIPIR, a modern ionosonde, and observed spread-F features from the ionograms recorded between 13:19~15:04 UT, i.e., 21:19~23:04 LT, on 26 October 2021. The observed ESF event lasted for approximately one hour and forty-five minutes. In Figure 3, the upper ionogram shows two traces of one-hop F-layer echoes, where the upper trace is weaker than the main trace and has higher altitudes with approximately 25 km differences at the start (13:19 UT) of the ESF event. Furthermore, the lower ionogram shows a weak range spread-F, which was recorded during the middle (13:49 UT) of the ESF event. We note that the spread-F frequencies ranged from ~1.7 MHz up to 11.5 MHz, which presents the top frequency of ordinary ionospheric echoes, i.e., foI . It is usually difficult to retrieve a critical plasma frequency $foF2$ from ionograms with ESF, but not difficult to retrieve foI . Multi-trace echoes could be interpreted as being due to the large-scale plasma depletion that happened before an ESF event. Meanwhile, the range-type spread-F indicates the existence of small-scale irregularities on the whole bottom side ionosphere.

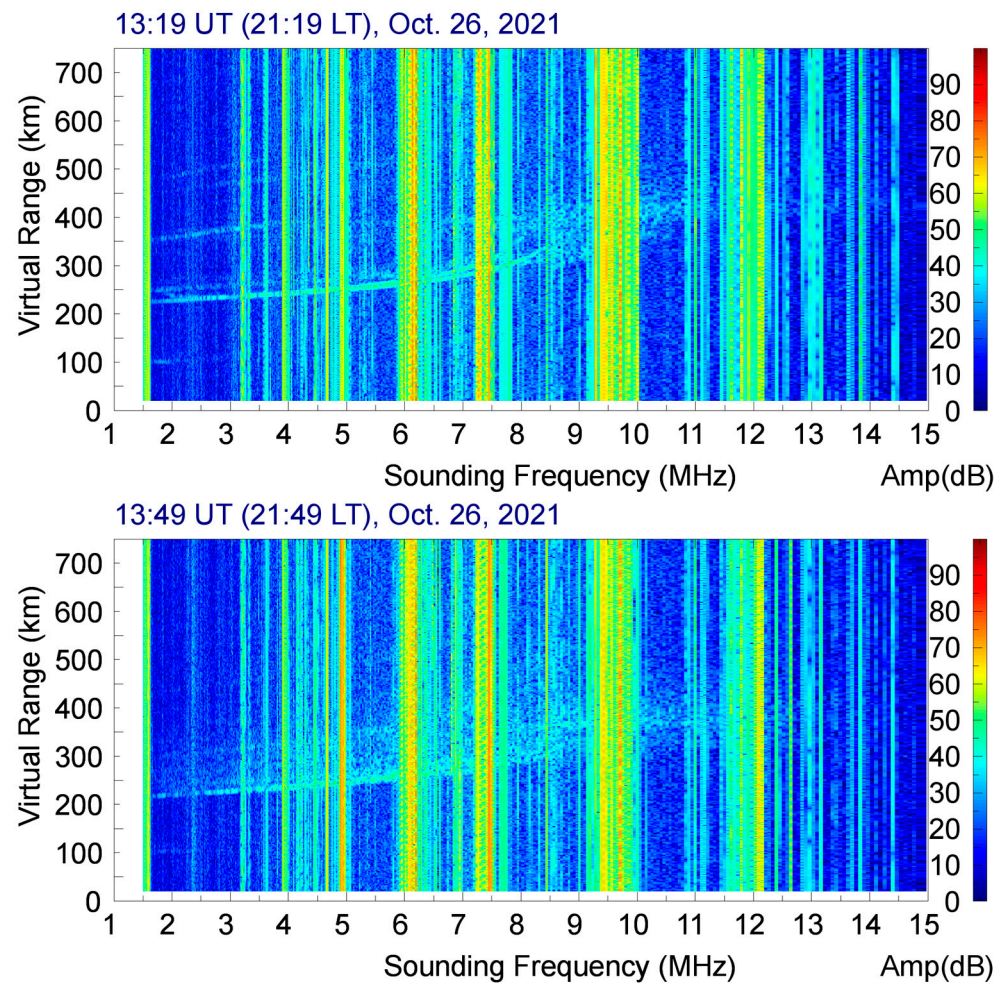


Figure 3. Two typical ionograms showing multi-trace echoes (**upper panel**) and weak range spread-F (**lower panel**) observed at the start (13:19 UT) and mid (13:49 UT) of an ESF event by the Hualien VIPIR on 26 October 2021. Note that the signals throughout all virtual ranges are radio frequency interferences from other radio sources.

Figure 4 shows the geographical geometry of the ionospheric pierce points (IPP) of the simultaneous GPS signal measurements at 14:42 UT on 26 October 2021, using the CWB GPS receiving network. The IPP altitudes were designed to be 300 km in accordance with the statistical peak scintillation or irregularity altitude retrieved from the FS7/COSMIC2 limb-viewing S_4 and/or N_e profiles, as shown in Figure 2. Furthermore, the IPPs were obtained at and limited by a minimum elevation angle of 45° from receivers to avoid multi-path signals. In this study, we define the vertical scintillation index VS_4 as the vertical component of the normalized variance of the signal power intensity I as follows:

$$VS_4 = \sin(\theta) \times \text{sqrt} \left(\frac{\langle (I - \langle I \rangle)^2 \rangle}{\langle I \rangle^2} \right), \quad (1)$$

where θ is the line-of-sight elevation angle from the receiver. We calculate VS_4 values by applying (1) and a 30-s duration window to 1-Hz L1-band signal amplitudes from the CWB GPS data archives. We note that the use of VS_4 to represent a vertical scintillation index is based on an assumption in which irregular N_e distribution is a function of altitude only along a transionospheric radio path. However, equatorial plasma bubbles are plume-like structures from low altitudes [4], and the shapes of bubbles are extended vertically upward and also stretched in the north-south direction along the magnetic field lines. Ref. [20] shows

that GPS RO observations with high S_4 values are much more likely to occur when the ray paths are distributed in certain bubbles and more nearly aligned with the magnetic field. The details of two-dimensional and even three-dimensional irregular N_e structures should be figured out in future studies. Meanwhile, we can assume the observing irregularities located at altitudes around 300 km to be the IPP altitude, and the corresponding FFZ scale sizes (D_F) of L1-band signals are between 239 and 275 m for elevation angles from 90° to 45° . We note that GPS satellites have orbiting velocities of approximately 3.9 km/s, and thus the corresponding IPP velocity is ~ 60 (80) meter/s at an elevation angle of 90° (45°) from the receiver. If we assume a frozen ionosphere, the resulting Fresnel frequencies f_F are between 0.18 and 0.2 Hz. Ref. [11] shows that, using extensive incoherent scatter radar observations from Jicamarca, the daytime westward drifts are significantly smaller than the nighttime eastward drifts, and during solar maximum, the maximum nighttime eastward velocity increases up to about 160 m/s. Even if we include a 160 m/s IPP trace component of plasma irregularity drift velocity, the resulting Fresnel frequencies f_F are approximately 0.66 Hz and are also lower than the 1-Hz sampling rate for the CWB GPS receivers. This means that the derived S_4 values from the CWB GPS data are at complete conditions. As a result, Figure 5 shows three developed structures on a two-dimensional VS_4 map taken at 13:24, 13:49, and 14:42 UT, which are approximately at the start, middle, and end of the scintillation and ESF event. Referring to Figure 4 and the bottom panel of Figure 5 based on the same CWB GPS data at 14:42 UT, we derive a two-dimensional extended VS_4 map deduced through relaxation by applying the red-black smoothing technique [21] on point-distributed VS_4 measurements. We execute one pass through the mesh updating the “red” cells (like the red squares of a checkerboard) and another pass updating the “black” cells (like the black squares) and so forth for two loops. It produces two more cell extents on derived VS_4 maps where the cell (latitudinal or longitudinal) resolution is 0.1° , determined approximately by the medium distance between neighboring GPS stations.

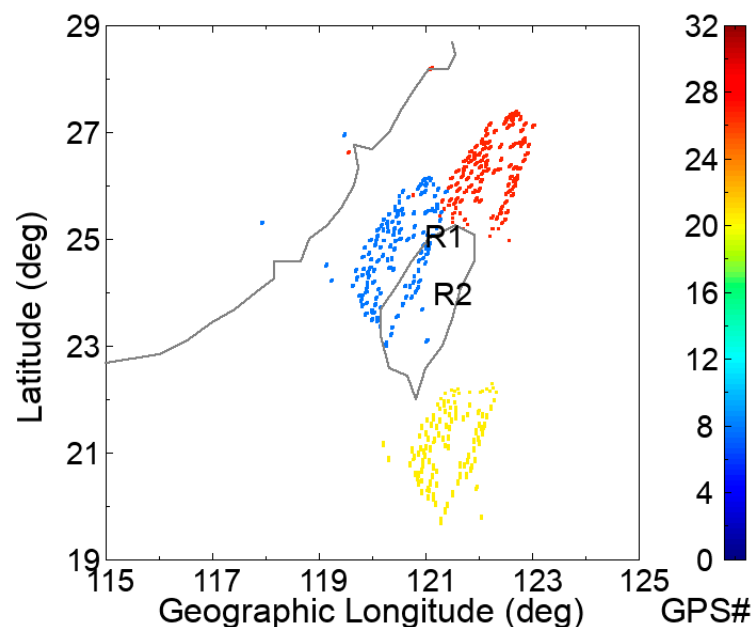


Figure 4. Geographical geometry of the IPPs of the simultaneous GPS signal measurements at 14:42 UT on 26 October 2021, and from 133 ground-based receivers located in Taiwan and the surrounding islands. The dots colored in light blue, yellow, and red show the IPP positions at 300 km altitudes for the lines of sights connecting GPS satellite #8, #21, and #27, respectively, which have a minimum elevation angle of 45° from receivers. The positions of another two software-defined GPS receivers located at Chungli (24.97°N , 121.19°E) and Hualien (23.89°N , 121.55°E), Taiwan, are shown and labeled by “R1” and “R2”, respectively.

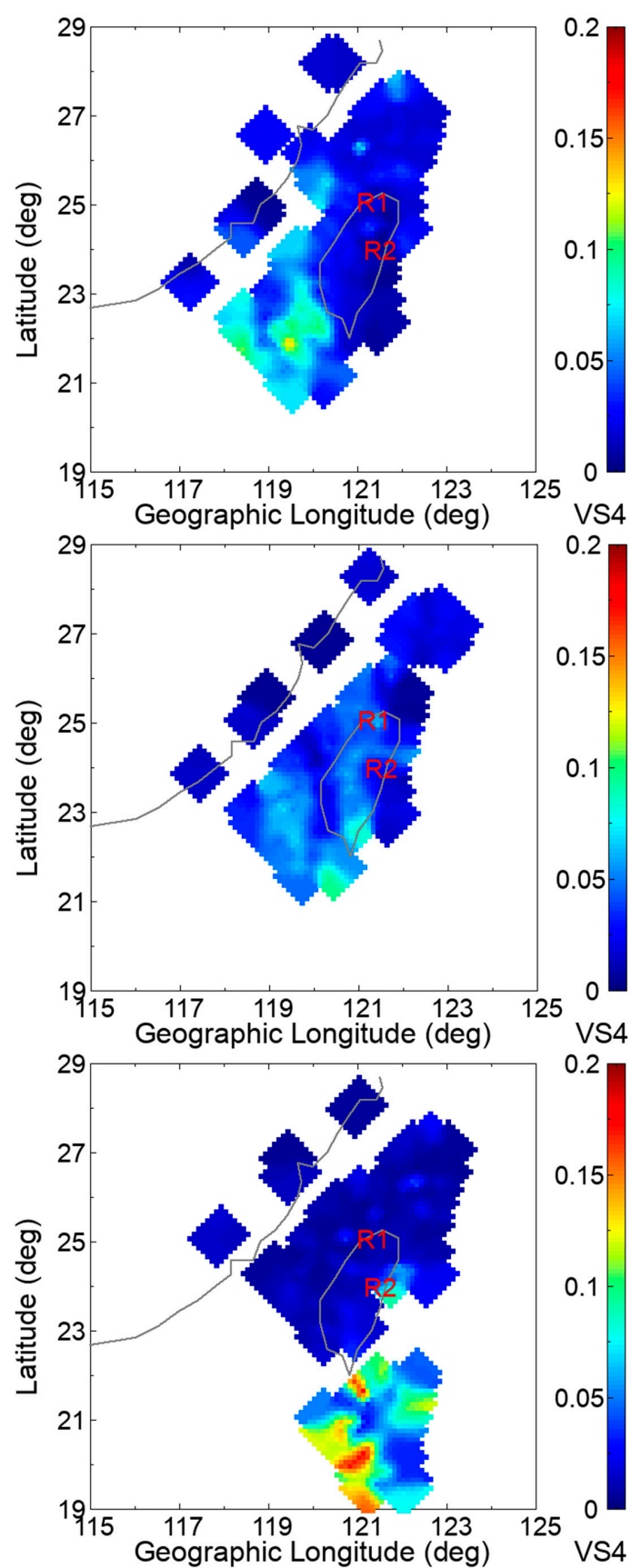


Figure 5. Three developed structures in two-dimensional VS_4 map taken at 13:24 (**upper panel**), 13:49 (**middle panel**), and 14:42 UT (**lower panel**) on 26 October 2021, and derived by the simultaneous GPS signal measurements from the CWB GPS receiving network.

It is now generally accepted that radio scintillation caused by ionospheric plasma irregularities can be characterized by fitting a power-law function with the spectral index p to the derived signal spectrum [2,22–24]. According to the scintillation theory and power spectra analyses [2,25], the intensity spectrum of weak and moderate scintillations and power-law ionospheric irregularities should have more or less a flat portion at low frequencies and start to roll off around the Fresnel frequency in the form f^{1-p} , where p is defined as the spectral index and is near 4 in the irregularity power-law relationship. Furthermore, the higher the spectral index, the stronger the scintillation intensity and the smaller the irregularity scale.

As described in the last section, we also operate two high-sampling, software-defined GPS receivers located at Chungli and Hualien, Taiwan separately to simultaneously receive GPS signals. The locations of the Chungli and Hualien software-defined GPS receivers are shown in Figures 4 and 5 and labeled by “R1” and “R2”, respectively. In this study, L1-band C/A code signal amplitudes were recorded at a sampling rate of 50 Hz and for a 70-s duration every five minutes. We obtain three L1-band signal scintillation patches recorded by the Chungli software-defined GPS receiver at different data segments, which are from 13:29 to 13:44 UT, 14:29 to 14:49 UT, and 13:44 to 14:19 UT on 26 October 2021, for GPS satellites #8, #21, and #27 signal observations, respectively. The derived VS_4 values are consistent with CWB GPS observation results and are from 0.19 to 0.25, 0.16 to 0.22, and 0.14 to 0.19 for GPS satellites #8, #21, and #27 signal measurements, respectively. Figure 6 shows the corresponding signal spectrums obtained via a Lomb periodogram algorithm [21]. We note that above approximately 1 Hz, the power spectral densities (PSD) are near the noise level where the minimum frequency of the noise level is defined as the deviation frequency of the signal intensity spectrum [26,27]. The 50-Hz sampling rate is approximately one order higher than the derived deviation frequency. Below 1 Hz, the PSDs are more or less a flat portion at low frequencies and decay from their maxima at a break frequency of f_B toward the noise level in an approximately linear fashion on the log-log scale shown. This indicates and confirms a power-law variation f^{1-p} of the plasma irregularity PSD with the frequency as discussed. We note that the spectrum break frequencies of f_B can be treated as the experimental Fresnel frequencies and are approximately 0.07, 0.15, and 0.12 Hz, and the derived spectral index p values are 3.57, 4.36, and 3.59 for the L1-band signal scintillation patches from GPS satellites #8, #21, and #27, respectively. Comparing with the corresponding IPP positions shown in Figure 4 and the derived VS_4 maps shown in Figure 5, we note that the area with a higher spectral index p has a stronger scintillation intensity. The spectrum analysis results of the L1-band signal scintillation patches recorded by the Hualien software-defined GPS receiver are similar to those from the Chungli system and are not shown in this study.

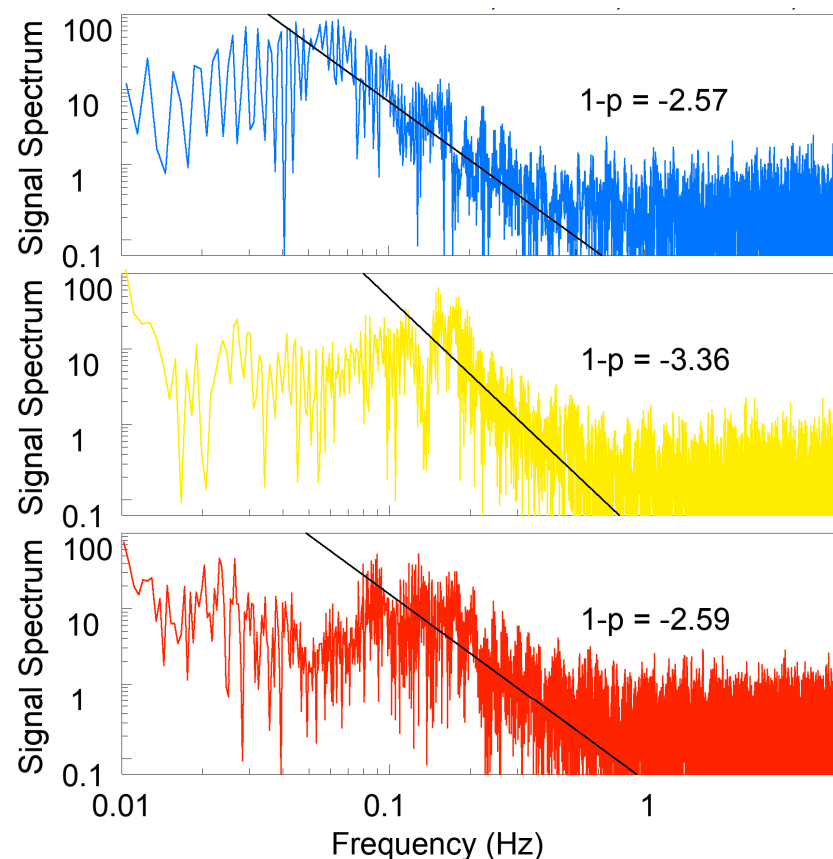


Figure 6. Power spectrums and their spectral index p values of the L1-band signal scintillation patches recorded by the Chungli software-defined GPS receiver from GPS satellites #8 (**upper panel**), #21 (**middle panel**), and #27 (**lower panel**). Three data segments are from 13:29 to 13:44 UT, 14:29 to 14:49 UT, and 13:44 to 14:19 UT on 26 October 2021, for GPS satellites #8, #21, and #27 signal observations, respectively.

4. Discussion

As mentioned in the Introduction section, at the times near and/or soon after sunset, an enhanced eastward electric field, i.e., PRE, causes the F-layer to move upward and develop plasma depletions, triggering the Rayleigh–Taylor instability. As a result, the plasma bubbles develop from the bottom side, and the instabilities cause ionospheric irregularities and radio signal scintillations and intrude into the higher altitudinal and latitudinal ionosphere.

In this study, a multi-station and multi-instrument system is organized and proposed for ionospheric scintillation and ESF specification in the Taiwan–Philippines sector. The FS7/COSMIC2 program can provide more than 5000 GPS/GLONASS RO observations per day within the region between the geographic latitudes of $\pm 40^\circ$, i.e., approximately seven RO observations per hour in the Taiwan–Philippines sector (between $20^\circ \pm 15^\circ\text{N}$ and $120^\circ \pm 15^\circ\text{E}$ geographic coordinates). From the FS7/COSMIC2 RO measurements on 26 October 2021, the observed or retrieved limb-viewing SNR, S_4 , and N_e profiles have been used to identify an ionospheric irregularity and scintillation event that happened from 13:30 to 15:00 UT, i.e., from 21:30 to 23:00 LT in Taiwan, and at magnetic quiet conditions. The results also show that the N_e irregularities and limb-viewing radio intensity scintillations are stronger and distributed into higher altitudes at the southernmost part of the Taiwan–Philippines sector, i.e., near the geomagnetic equator, compared to those near the sector center (geomagnetic latitude $\sim 10^\circ\text{N}$). Furthermore, as shown in the right panel of Figure 2, the scintillation altitudes of the RO observation #4 and even observations #5 and #6 were distributed at an altitude range of ~ 100 km only and around the F-layer N_e peaks. This

could indicate that the irregularities at higher latitudes are the latitudinal mapping-out facts from lower latitudes, and that there are stronger irregularities around F-layer peaks because of greater conductivities.

More evidence of the longitudinal extent of plasma irregularities is also shown by the two-dimensional VS_4 maps derived from the CWB GPS data archive. As shown in Figure 5, the significant scintillation event that happened on 26 October 2021, was also observed by the CWB GPS receiving network. The series of VS_4 maps shows plasma irregularities distributed with a stronger intensity at lower latitudes and when moving eastward. This indicates that the FS7/COSMIC2 could provide ionospheric irregularity and scintillation observations scanning in different limb-viewing, i.e., near-vertical, directions, and more than one hundred and thirty ground-based GPS receivers operated by the CWB could do it in horizontal directions.

We note that the ground-based CWB GPS signal observations have a sampling rate of 1 Hz, which is higher than the possible maximum Fresnel frequencies f_F of approximately 0.66 Hz and can thus complete the scintillation index S_4 determination. However, the 1-Hz sampling rate is not enough for irregularity spectral index determination, which needs the rate to be approximately one order larger than its Fresnel frequency. In practice, spectrum analyses applied to the high-sampling, software-defined GPS receiver measurements conform to a power-law variation f^{1-p} of plasma irregularity PSD with frequency. Meanwhile, the derived spectrum break frequencies f_B are more or less 0.1 Hz, which are all less than the corresponding Fresnel frequencies f_F of approximately 0.2 Hz for a frozen ionosphere. This indicates that the targeted plasma irregularities moved northward too and had positive velocity components along the IPP-tracing directions to decrease the relative radio-scanning speed and the experimental Fresnel frequencies obtained by the derived f_B values. In sum, integrating the observations from the FS7/COSMIC2, the CWB GPS receiving network, and two software-defined GPS receivers located in Taiwan, the experimental results show that the targeted plasma irregularities moved eastward and northward. Furthermore, the smaller the irregularity scale, the higher the spectral index and the stronger the scintillation intensity at lower latitudes on the aimed irregularity feature.

As described, ESF features usually accompany equatorial plasma bubbles and can also be observed and scaled from ionograms, as shown in Figure 2. Figure 7 shows the time variations of the virtual ranges of ionospheric echoes at different sounding frequencies f_s of 1.72, 3.08, 4.72, 5.65, and 7.15 MHz from the Hualien ionograms recorded on 26 October 2021. Figure 7 also shows the corresponding temporal profile of scaled foI , which is approximately equal to $foF2$ without spread-F and/or sporadic E features but higher than $foF2$ with spread-F features. We note that the sunset time of the day was approximately 18:30 LT, i.e., 10:30 UT, at Hualien, Taiwan, and at a 300 km altitude. As shown in Figure 7, the spread-F features happened and were observed between 13:19–15:04 UT, i.e., 21:19–23:04 LT. Furthermore, after 15:04 UT, i.e., the end of the ESF event, the foI ($foF2$) values decreased, and the virtual heights of the fixed-frequency ionospheric echoes increased as usual facts of nighttime ionograms. Before 13:19 UT, i.e., the start of the ESF event, the foI ($foF2$) values show more or less a flat portion, but the virtual heights of fixed-frequency ionospheric echoes decreased except for those at a sounding frequency of 1.72 MHz, which are actually one-hop and two-hop sporadic E echoes and thus almost invariant in virtual heights. This indicates that after sunset and before the ESF event, the peak ionospheric N_e values were approximately the same but the ionospheric N_e values at the bottom side ionosphere were increased. This could be due to a strong PRE, i.e., eastward electric field enhancement that happened near or after sunset on the day and produced an equatorial fountain effect. As a result, the equatorial ionosphere moved upward, developed steep density gradients and large-scale plasma depletions in the bottom side F-region and became unstable, triggering the R–T instability. Meanwhile, ionospheric plasma moved out along the geomagnetic field line and from the magnetic equator to higher latitudes. In this study, such an equatorial fountain effect was not strong enough to increase the peak N_e s and $foF2$ s but was strong enough to increase the N_e s at the

bottom side ionosphere in the low-latitude region, e.g., the Taiwan area. We found that a post-sunset decrement of the virtual heights of fixed-frequency ionospheric echoes could be a good precursor for post-sunset scintillation and ESF events.

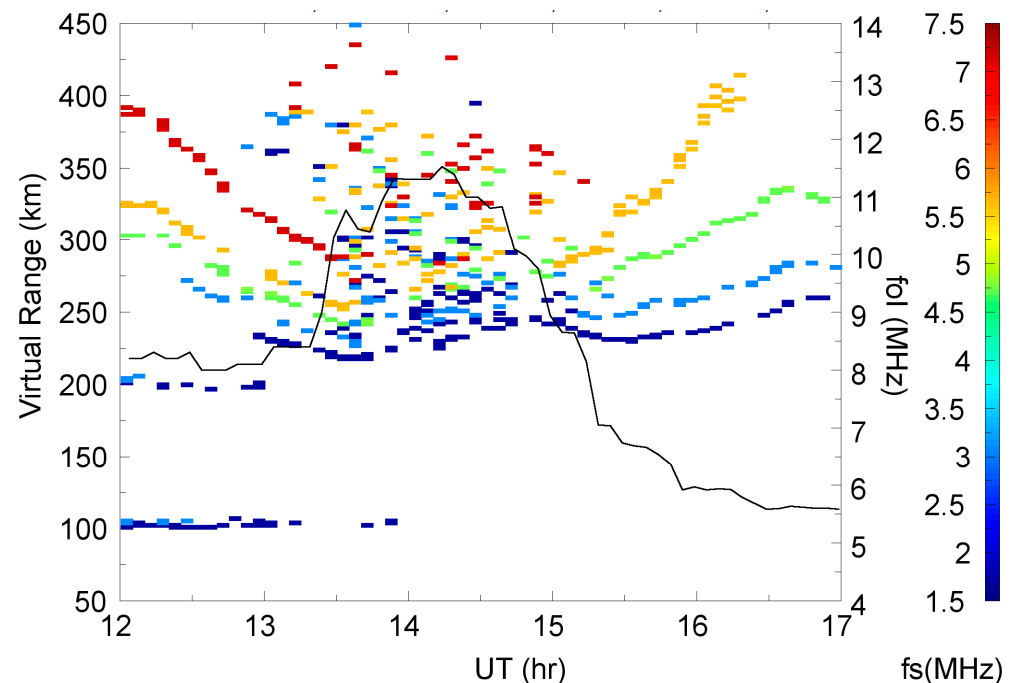


Figure 7. Time variations of virtual ranges (referring to the left y -axis) of ionospheric echoes at different sounding frequencies f_s of 1.72 (dark blue), 3.08 (light blue), 4.72 (green), 5.65 (orange), and 7.15 MHz (red) from the Hualien ionograms recorded on 26 October 2021. Another temporal profile of scaled foI is also shown and referring to the right text. Note that the spread-F features were happened between 13:19~15:04 UT, i.e., 21:19~23:04 LT in Taiwan.

5. Conclusions

Ionospheric irregularities and scintillations and their associated motions in the Taiwan–Philippine sector have been observed and specified by the FS7/COSMIC2 data, the VIPIR located at Hualien, Taiwan, 133 ground-based GPS receivers located in Taiwan and the surrounding islands, and two high-sampling, software-defined GPS receivers. The integrated system has the potential to provide scintillation intensities, zonal drift measurements, and even three-dimensional irregularity structures. We also suggest that a post-sunset decrement of the virtual heights of fixed-frequency ionospheric echoes could be a good precursor for post-sunset scintillation and ESF events. In the future, we expect to identify the ionospheric conditions in the Taiwan–Philippines sector that led to the onset of plasma/R–T instabilities and to forecast the growth and the timing/duration of each instability. An examination of these instabilities will form the basis for the forecast of the timing and severity of (GNSS) radio scintillations.

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Data Availability Statement: The FS7/COSMIC2 “ionPhs” data can be downloaded from the COSMIC Data Analysis and Archive Center (CDAAC, <http://cdaac-www.cosmic.ucar.edu/> (accessed on 1 December 2021)) and the Taiwan Analysis Center for COSMIC (TACC, <http://tacc.cwb.gov.tw/cdaac/> (accessed on 1 December 2021)).

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