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Airglow observed by a full-band imager together with multi-instruments in Taiwan during nighttime of 1 November 2021

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Abstract

This study demonstrates an innovative approach of using a full-band chromatic all-sky imager, routinely operational for monitoring sky conditions at Lulin observatory (23.5°N, 120.9°E, 12.5°N magnetic latitude), Taiwan, to investigate equatorial plasma bubbles (EPBs). Distinct north-south aligned EPB depletions are identified by decomposing the color-scale images to respective red (centered at 630 nm) and green (520 nm) channels, where blue channel (470 nm) helps for background suppression. The intense EPBs, drifting eastwards at 60-100 m/s velocity, are also associated with reduced total electron content (TEC) values; increased ROTI (rate of TEC index);
remarkable range spread-F; and prominent fluctuations in Doppler frequency shifts as well as FORMOSAT-7/COSMIC-2 electron density/S4 scintillation profiles. The results show that a full-band chromatic imager offers a cost-effective alternative to investigate the EPBs usually detected in OI 630.0 and 557.7 nm airglow emissions.

1. Introduction

All-sky imaging of airglow depletions with 630.0 nm and 557.7 nm narrowband interference filters has been widely employed to study equatorial plasma bubbles (EPBs) associated with Equatorial Spread-F (ESF) irregularities (Weber et al., 1978; Mendillo and Baumgardner, 1982; Taylor et al., 1997; Fagundes et al., 1997, 1999; Sahai et al., 2000; Kelley et al., 2002; Makela et al., 2004, 2010; Makela, 2006; Mendillo et al., 2005; Rajesh et al., 2007, 2010; Liu et al., 2011; Shiokawa et al., 2015; Fukushima et al., 2015; Okoh et al., 2017; Ghodpage et al., 2021; Wrasse et al., 2021). The irregularities are generated at the magnetic equator when suitable conditions exist at the F-region bottom-side in the post-sunset period and manifest themselves as dark bands of intensity depletions in the airglow images taken from equatorial or low-latitude stations (Weber et al., 1978; Mendillo et al., 2005). The depletions are aligned along magnetic field lines, and usually drift eastward with the ambient plasma velocity (Mendillo and Baumgardner, 1982; Sinha et al., 2001; Martinis et al., 2003; Pimenta et al., 2003; Sarudin et al., 2020). The regions corresponding to the depleted airglow intensity also exhibit reduced total electron content (TEC) values, have severe TEC variations, namely rate of TEC index (ROTI) (Chu et al., 2005; Nishioka et al., 2008; Cherniak and Zakharenkova, 2016; Oliveira et al., 2020; Rajesh et al., 2022), and yield prominent HF (high frequency) Doppler frequency shift fluctuations (e.g., Chum et al., 2014; 2016).

Taiwan, located under the northern crest of the equatorial ionization anomaly (EIA), is an ideal place to image airglow depletions, where one can see high altitude depletions which often appear bifurcated. Chow et al. (2002) reported EPBs that attain apex altitudes of about 1500 km, and drift eastwards at speeds of ~115 m/s during the post sunset period in higher solar activity conditions. Liu et al. (2011) examined the long-term characteristics of EPB observations over Taiwan, reporting new features of secondary instabilities on both walls of the bubbles and the evidence for the appearance of Y-shaped bifurcations. Rajesh et al. (2017) investigated the inhibition of EPB occurrence over Taiwan during the St. Patrick’s Day storm in 2015. Such all-sky measurements are usually carried out by using airglow imagers made of sophisticated telecentric optics with high precision components, narrow-band interference filters, and
deep cooled CCD (charge coupled device) cameras with very high quantum efficiency and extremely low thermal and readout noises (e.g., Baumgardner et al., 1993; Shiokawa et al., 1999), making their installation and maintenance extremely costly.

In recent years, there have been efforts to improvise the optical design of all sky imagers to develop low-cost systems that could be easily deployed and re-located to different places. Hosokawa et al. (2020) introduced a miniature single-band (630.0 nm) all-sky imager consisting of a low-cost CCD camera used for video recording, a fisheye lens and a band-pass filter, which can be controlled and operated by using open-source operating system and frame capturing software. By using such a simple design, they were able to image EPBs, which were also compared with concurrent observations made by traditional imager, though dedicated filters are still required to isolate the desired emission lines. Meanwhile, images of the night-sky taken by using chromatic RGB (red-green-blue) cameras have been used to identify the contributions from visible nightglow emissions (e.g., Christensen et al., 2016; Mikhalev et al., 2016). On the other hand, airglow in the mesosphere and the F-region ionosphere was captured on the limb of the Earth with a digital single-lens reflex camera from the ISS (International Space Station) by astronauts (Hozumi et al., 2016). With the advances in the CMOS (complementary metal oxide semiconductor) technology, it is now even possible to use the commonly available commercial cameras to capture the night emissions that fall within the visible bands.

The novel methodology applied in this study introduces the potential of extracting the night-sky emissions containing the signatures of the airglow bands used in the investigation of EPBs by utilizing the RGB image frames obtained from a surveillance camera consisting of a wide-angle lens and a CMOS sensor, without any additional filter being necessary. An example of an intense EPB event on 1st November 2021 is used to illustrate how the video streams from such an all-sky camera intended for routinely monitoring the sky conditions at Mt. Lulin astronomy observatory (23.5°N, 120.9°E, 12.5°N magnetic latitude) in Taiwan could be used to retrieve the airglow signatures corresponding to the plasma density variations by the EPB. The observations are compared with TEC and ROTI estimated from the dense GNSS network, ionosonde, and Doppler shift measurements, as well as FORMOSAT-7/COSMIC-2 (F7/C2) radio occultation (RO) data over Taiwan to find the possible factors that influence the generation of the EPBs in the low solar activity conditions.

2. Instruments and methods
Mt. Lulin, with an altitude of about 2.8 km above the mean sea level, is ideal for imaging the faint emissions from the night sky with much less background light pollution (e.g., Liu et al., 2011). This study makes use of the surveillance camera for routinely monitoring the sky conditions at the Lulin Astronomy Observatory, set up by the Graduate Institute of Astronomy of National Central University, Taiwan. The system consists of a 180° front-end lens and a CMOS back illuminated camera and takes images approximately every 1-minute interval. Figure 1a illustrates the sky coverage of the monitoring camera projected to an altitude of 250 km, where the wide view angle allows the camera to image the light emanating from a geographical area with a diameter of about 10°. The location of Lulin is marked at the center of the image. The figure also shows the locations of the reflection points of Doppler sounders, ground-based GNSS receivers, and the Taiwan ionosonde used in this study.

Figure 1b shows the spectral response curves of the CMOS sensor used, where the three peaks corresponding to the RGB channels are respectively centered at 630, 520 and 470 nm wavelengths. The strategy of finding the EPB characteristic is based on the spectral response curves. Note that the spectral peaks of the red and green channels overlap with the 630.0 and 557.7 nm airglow emissions. Hence, the idea is to separate the grayscale image into RGB channels and examine the images for possible airglow characteristics in the respective color channels. However, in the absence of dedicated filters, it is challenging to establish if the measured intensity includes the contribution from the airglow emissions. This could be overcome if the images include any distinct patterns that are specific to the airglow emissions, and an EPB event is the most suitable geophysical phenomenon to support the adopted strategy.

An example of the full-color (FC) grayscale image taken on 1 November 2021 at 2050 LT is displayed in Figure 2. The figure also shows the red (R), blue (B) and green (G) channels extracted from the FC image. The FC and R images show very faint dark structures elongated in the north-south (N-S) direction, resembling the typical EPB depletions in airglow images. This pattern is absent in the B image and could not be distinguished in the G image. In the right column, when the B image is subtracted the EPB structures become more prominent in the R-B image, and though much weaker, could also be discerned in the G-B image. Figure 2 thus illustrates the potential of using an ordinary surveillance camera to extract the signatures of plasma depletions, which otherwise requires very sophisticated and costly optical instrumentation.

3. Observations
A sequence of the R-B and G-B images revealing the development of EPBs in the night of 1 November 2021 is given in Figure 3. It can be seen that a weaker EPB exists even in the image at 1900 LT to the south-west of Taiwan. In the subsequent images plotted, fresh EPB emerge from the western longitudes, which also appear much more elongated in the N-S direction, encompassing the entire Taiwan by 2100 LT and reaching latitudes of 25.5° N, corresponding to an apex altitude over 1000 km. The intense EPB activity in this night continues to the post-midnight hours till about 0200 LT. Though the G-B images also show nearly identical EPB patterns as in the R-G image, the structures are much weaker and hence only the R-B images are used in this study to further investigate the characteristics of the observed irregularities in this night.

We examine the zonal cross-section of the R-B images at the latitude of the Lulin Astronomy Observatory (120.9°E, 23.5°N) to find the eastward drift speed of EPBs. The eastward movement is inferred by constructing intensity Keograms, where the zonal slices of the observed intensities at the latitude corresponding to the imager center (i.e., the latitude of Lulin) are plotted as a function of time. The slopes of the individual EPBs in such time-longitude maps provide the corresponding zonal drift speeds. The consolidated Keogram in Figure 4 reveals three prominent EPB patterns drifting eastward over the Lulin Astronomy Observatory with speeds of 89-91, 51-68, and 56-78 m/s at about 2000, 2100, and 0000 LT, respectively. It seems that the western wall of the EPBs tends to yield slower speeds. Moreover, overlapped images show that in general, when the EPBs appear, the TECs and ROTIs decrease and increase, respectively. It should be noted that, for the EPB at 2000 LT, the TEC and ROTI appear to vary little though the R-B intensity shows weak but distinct depletion. It is possible that the observed EPB could still be evolving to sufficiently higher altitudes of 325-375 km (cf., Liu et al., 1996) to significantly impact the GNSS observations, whereas the R-B intensity variations are mainly sensitive to EPB below the F-peak at about 250 km altitude (cf., Takahashi et al., 1990). Thus, though still seen as slight TEC decrease, the scale of ROTI variation caused by the EPB could be less distinguishable. Such mismatches in the two observations could also arise due to possible differences in the line-of-sight geometry of the GNSS satellite and receiver ray path with respect to the EPB.

Figure 5 compares the time sequence of R-B intensity representing the variations of OI 630.0 nm emission with corresponding ROTI values, Doppler frequency shifts at the sounding frequency of 5.5 MHz at the six receiving stations, virtual heights from the ionograms at the sounding frequencies of 5-6 MHz and selected ionograms showing Spread-F. The three EPBs appear at about 2000-2100 LT, 2130-2230 LT, and 0020-0130 LT, where the first EPB could be barely detected in the measurements at the given
locations. For each EPB, especially for the latter two, as the OI 630.0 nm intensity (ROTI) starts reducing (enhancing), reaching a minimum (maximum) value and returns to the background level, the Doppler shift fluctuations vary from 1.5 Hz to -1.5 Hz; the virtual heights fluctuate; with range spread-F in the corresponding ionograms.

It can be seen from the figure that the irregularities yield about 60-70% reduction in the emission intensity with respect to the background, indicating a corresponding decrease in the plasma density. The Doppler shifts of 1.5, 0, and -1.5 Hz correspond to those irregularities that are approaching, existing right overhead, and drifting away from the reflection points. The local-time variations of the ionosonde echoes in the sounding frequency range of 5-6 MHz show that the virtual altitudes of the irregular regions causing the Doppler shifts are about 250-300 km, which suggests that the true reflection points are at about 200 km altitude.

This remarkable EPB event was concurrently detected in the space-based RO TEC measurements and S4 indices by F7/C2, further revealing the altitude distribution of the irregularities. Figure 6 displays selected slant TEC profiles and S4 profiles of radio occultation that overlap within the all-sky image FOV (field of view) at 2102, 2114, 2131, 2317, and 2319 LT. A 21-point sliding window is applied on the TEC values, constructing a mean profile for each measurement, and the TEC deviation (ΔTEC) is obtained by subtracting the mean profile from the corresponding observations. Note that the 10-sec S4 profiles have been interpolated to 1-sec resolution by using cubic splines. When the RO tangent locations and EPBs overlap, both ΔTEC and S4 profiles significantly fluctuate, as seen for the ΔTEC and S4 profiles between 175 and 400 km altitude at 2102 LT and the ΔTEC between 140 and 360 km altitude at 2131 LT. By contrast, when there is no overlapping, no obvious fluctuations in the ΔTEC and/or S4 profiles could be observed (e.g., at 2114, 2319, and 2317 LT).

4. Discussion and Conclusion

The novel method applied here to separate the grayscale image (FC) to R, G, and B channels, and then subtracting the B image to reduce the background noise offers a cost-effective alternative to set-up a network of such imagers to regularly monitor the development and evolution of plasmas depletions. The fact that distinct EPB features could be deduced in the observed images confirm that the spectral response of the CMOS sensor used indeed captures the airglow emissions coming from the ionospheric altitudes. The measurements thus offer a unique opportunity to examine the 557.7 and
630.0 nm intensity variations by using a simple and innovative method as applied in this study.

It is worth noting that almost identical EPB patterns are seen in both the R-B and G-B images, though in the latter such structures appear only in the early evening hours. While it is common to observe EPBs in 630.0 nm images, due to the intense mesospheric contribution (Shepherd et al., 1995; 1997), EPBs are rarely observed in 557.7 nm airglow observations (Fagundes et al., 1995; Mendillo et al., 1997; Takahashi et al. 2001). Based on simulations, Rajesh et al. (2007) noted that the thermospheric component of 557.7 nm could be significant in the late evening hours in solar maximum. The current observations show EPBs in the G-B images in the early evening hours, which disappear by 2130 LT (Figure 3), suggesting that the thermospheric component of 557.7 nm is not effectively masked by the mesospheric emission in the early post-sunset hours. Note that the simulations of Rajesh et al. (2007) indicate relatively stronger thermospheric 557.7 nm emission in the early evening hours in solar minimum conditions (their Figure 3), which appears to prolong a couple of hours in the deep solar minimum conditions during these observations. Meanwhile, it should be noted that the central wavelengths of green and red channels are 520, and 630 nm, respectively. The 520 nm central wavelength of the green channel might limit the 557.7 nm component in the observations, while the 630 nm central wavelength of the red channel is suitable to observe 630.0 nm airglow emission.

The coordinated observations reported in this study depict the evolution of EPBs from a combination of unique measurements involving ground- and space-based observations, thus allowing to investigate the horizontal and vertical characteristics of EPBs. While the Doppler measurements, ionosonde, and GNSS ROTI barely detects the first EPB around 2030 LT, the R-B images are essential to conclusively identify this EPB that strengthens to the eastern longitudes of Taiwan, highlighting the important role of all-sky observations in such coordinated investigations. The all-sky observations are also essential to infer the zonal evolution of the EPBs. The larger eastward velocities at the eastern wall compared to the western wall (Figure 4) may result from an increasing westward tilt of EPBs with time, which would yield relatively smaller zonal slopes at the western edge in a time-varying frame compared to the eastern edges.

The positive Doppler shifts show that the regions of reduced (enhanced) airglow intensity (ROTI) are predominantly associated with approaching irregularities, while as the EPBs move away from the reflection points, a reversal of the irregularities motions is evident (Figure 5). This pattern of positive Doppler shifts of the approaching ESF
oblique traces, which alters to negative Doppler shifts as the structure drifts away, is consistent with previous Doppler spectral measurements (Chum et al., 2014; 2016). The zonal drifts speeds estimated from these oblique traces as formulated by Chum et al. (2014) are respectively 66 m/s (at 2200 LT) and 56 m/s (at 0100 LT), agreeing well with all sky observations (Figure 4).

The coincidence of RO profiles with the EPB locations further emphasizes the importance of all sky observations to correctly understand the observed vertical fluctuations in the TEC/S4 profiles (Figure 6). The altitude regions with strong fluctuations in the RO profiles depend on the distribution of the corresponding tangent location with respect to the EPB geometry. Thus, an RO profile would yield strong fluctuations at the tangent altitudes where the ray path trans-pass the EPB regions and not necessarily represent the altitudes where severe irregularities reside. Such concurrent observations could facilitate better geolocation of the irregularities that yield fluctuations of the RO observations.

The EPBs reported here corresponds to a period of weaker solar activity, where such irregularities reaching apex altitudes of ~1000 km are rare (e.g., Chou et al., 2020). This EPB event follows a glancing impact of a coronal mass ejection (CME) at about 1000 UT on 31 October 2021, which triggered a minor G1 geomagnetic storm. The disturbed conditions that persisted might have favored the seeding of EPBs. With the on-going ascending solar phase, the observation strategy adopted here offers the promising prospect of making coordinated measurements by installing meridional chains of such all-sky cameras over nearby longitudes, thus being able to monitor the evolution of EPBs from their onset, till decay. Note that only basic image processing is applied in this study, and more sophisticated analysis such as integrating observations over selected duration, further background removal using average subtraction etc. could further improve the visualization of EPBs.

In conclusion, this study offers a unique observation strategy, which can be very effectively used to monitor and investigate the occurrence of equatorial plasma bubbles with ordinary surveillance cameras. The results demonstrated here highlight the potential of the methodology to observe EPBs even during deep solar minimum conditions. The coordinated Doppler measurements, ionosonde, and the vertical information from F7/C2 occultation profiles show that the observed EPBs are predominant irregularities occurring over 200-300 km altitudes.

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**Figure 1.** The Lulin all sky imager and ground-based observations. (a) Locations of the all-sky imager (ASI) at Lulin Observatory (pink rectangle), reflection points of the Doppler sounding systems (white triangles), ionosonde (pink asterisk) and the ionospheric piercing points (IPPs) of GNSS receivers (dots). The figure also shows an example of the full-band all-sky image observed at 1250 UT (2050 LT) on 1 November 2021 and the colored dots stands for the vertical total electron content (TEC) values from the GNSS measurements. (b) The spectral response of the CMOS sensor used to record the sky images (Source: https://zwoasi.com/media/2016/09/IMX174-COLOR-1-1.jpg). The central wavelengths of blue, green, and red channels are 470, 520, and 630 nm, respectively.
Figure 2. Images of the full color (FC), red (R), green (G), and blue (B) bands, as well as differences of red-blue (R-B) and of green-blue (G-B) observed 2050 LT on 01 November 2021. The toy dog at the southwest south edge is set to block the unwanted light spot.
**Figure 3.** Sequence of (a) R-B and (b) G-B images at every 30-minute from 1900 LT-0230 LT in the night of 1-2 November 2021. The magenta dashed line stands for the latitude of Lulin Observatory.

**Figure 4.** Eastward velocity of EPBs observed in the night of 01-02 November 2021. (left) Keogram constructed from the R-B images at the latitude of Lulin observatory during 1900-0200 LT. The red lines highlight the edges of EPBs and the respective zonal speeds estimated are marked on the image. The Keogram overlapped with the corresponding (middle) TEC and (right) ROTI values from the GNSS measurements are also shown.
Figure 5. The 630 nm airglow intensity, ROTI, and Doppler frequency shifts at the locations of the six reflection points during 1900-0200 LT in the night of 01-02 November 2021. The bottom panels give the virtual heights at 5-6 MHz sounding frequencies in the ionograms and five selected ionograms at 2100, 2200, 2330, 0100 and 0200 LT on this day. Note that the duration of spread-F is denoted in the top panels by using red cross and asterisk symbols.
Figure 6. Radio occultation profiles of TEC, TEC gradient, and S4 index observed by FORMOSAT-7/COSMIC-2 at 2102, 2114, 2131, 2319, 2317 LT on 1 November 2021. The right panels give the tangent locations of the RO measurements overplotted on the corresponding R-B images.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.