Remote sensing of ionospheric plasma bubbles using GPS/GNSS

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Abstract
The equatorial plasma bubble (EPB) is plasma depleted region of the ionosphere which affects the trans-ionospheric communication/ navigation to great extent. In this paper occurrence and characteristic of plasma bubbles over the Hong Kong during deep solar minimum 2007-2009, has been studied using the GPS data from continuously operating reference stations (CORS) network. Generally plasma bubble occurrence is expected to be maximum during the equinox season but for the deep solar minimum period from 2007 to 2009 unusual seasonal occurrence in plasma bubbles has been observed and found to be a maximum during the June solstice instead of equinox. The diurnal characteristics of plasma bubbles have been studied and their occurrences are found to be more prominent during the nighttime hours. Moreover the daytime EPBs observations are also noticed but their occurrences are found to be occasional. The observed daytime plasma bubbles are expected to be generated in the post-midnight hour at higher altitude and can survive until the daytime. The latitudinal dimensions of observed plasma bubbles during 2007-2009 are found to be dominant in 200-400 km range.

Keywords—*Equatorial ionosphere, plasma bubbles, solar deep minimum*

I. INTRODUCTION

Equatorial Plasma Bubbles (EPBs) are detrimental for trans-ionospheric radio communication and have been studied for decades [1-2]. It is now understood that EPBs form due to generalized Rayleigh-Taylor instability mechanism occurring in the night-time ionosphere. On occasions, EPBs grow to reach altitudes of ~1500 km over the dip equator [3]. The EPBs are expected to cause interruptions to trans-ionospheric radio signals transmitted from GNSS (global navigation satellite system) by means of producing amplitude and phase scintillations. Therefore prediction and forecasting of EPBs has been the subject of significant research efforts over the past decades [4-11].

In the past years several techniques such as: ionosonde [12-13], topside sounder [14], radio scintillation [4, 6], air glow observation [15] as well as satellite based measurements [16] have been used to study the characteristics of the plasma bubble. In the recent years, GNSS has become important tool for ionospheric plasma bubble study [10, 17] because of its growing application in civilian and military applications.

In this study the data recorded over 12 ground based GPS (global positioning system) stations in Hong Kong region, during deep solar minimum from 2007-2009, has been used to study the occurrences and features of EPB. Generally more EPB occurrences are expected during the high solar activity years but in this study the long lived deep solar minimum 2007-2009 has been selected for studying the EPB occurrence which could add significant finding to research community which is hidden for the high solar activity. The method of data analysis is presented in section II and results & discussion in section III. Finally the results are summarized in section IV.

II. METHOD OF DATA ANALYSIS

The GPS data recorded over the Hong Kong from CORS network has been analyzed. This network called Hong Kong Satellite Positioning Reference Station Network (SatRef), consists of 6 continuously operating reference stations (CORS). It was established in 2001 by the Survey and Mapping Office (SMO) of Lands Departments, the Government of Hong Kong Special Administrative Region (HKSAR). This network was expanded to 12 GPS stations in 2004 (Fig.1a). The geographic and geomagnetic coordinates of these GPS stations is listed in table 1. The observed area of the ionosphere by the SatRef network can be defined by the ionospheric pierce point (IPP) of all observed satellites. The IPP is the point where the line of sight signal between GPS satellite and the ground GPS receiver intersects the thin, uniform-density shell (single layer model of the ionosphere) at the altitude around 350 km. The IPP tracks of all satellites against 0000-2400 UT (Hours) with elevation angle above 20 deg. observed on 05 May 2007 is shown in map (Fig. 1b). From this figure we can see the ionosphere observation area is about 14 to 29º N in latitude and 105 to 124º E in longitude.

In this study the slant total electron content (STEC) has been estimated from dual-frequency GPS observation data using the equations described elsewhere [18-19]. An equatorial plasma bubble can generally cause a sudden change of the slant or vertical TEC value, which is followed by a recovery when the satellite-to-receiver ray path no longer propagates through the bubble. Based on the above feature, a bubble can be detected from STEC data using the method described by Portillo et al. [20]. According to this method first STEC are derived from GPS observations; then a best polynomial fit to STEC is made (see Fig. 2a) with a window size of 15 min; subsequently, the values by subtracting the fitted STEC curve from the original STEC curve can be obtained as dSTEC (Fig. 2b). The difference between the maximum and minimum values is used as indicator for the occurrence of bubble and it will be called depth of the plasma bubble used in present study. The STEC depletions observed from a PRN with magnitude greater than 5 TECU and apparent duration between 10 min and 180 mins are considered as a plasma bubble [20]. In this study, this method has been used to identify the EPB occurrence over Hong Kong during the deep solar minimum 2007-2009. Figure 2 shows a typical case of the plasma bubble observed by PRN 05 over Hong Kong GPS station HKST on 27 June 2007 (quiet day with kp <4). It is clearly seen that three plasma bubbles were observed by PRN 05 with durations 28, 35 and 12 minutes and STEC depletion (or depth) 17.91 TECU, 18.17 TECU and 14 TECU respectively. To study the monthly, seasonal and annual occurrences of EPB only geomagnetic quiet days ($Kp \leq 4$) from 2007-2009 are considered for the analysis.

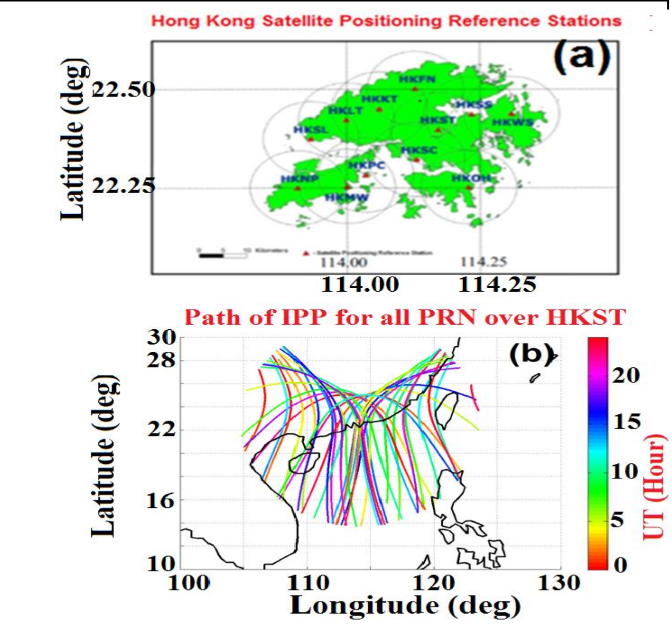

Figure 1: (a) Map showing the location of ground based GPS station established under Hong Kong local GPS Network (b) Map showing IPP tracks of all GPS satellites observed on the day of 5 May 2007.

III. RESULTS AND DISCUSSION

To study the local time occurrence of EPB, we have analyzed the percentage of EPB occurrence against 0-24 local time hour for each year from 2007-2009 which is shown by bar diagram in Figure 3. Generally EPB occurrences are the most frequent during nighttime hours (1900-2400 hours) than the daytime throughout 2007-2009. Apart from the nighttime, the daytime EPB have also been observed but are smaller as compared to nighttime. The diurnal occurrence of EPB is found in agreement with those reported in previous works [10, 21]. Most of the EPBs are developed in late night i.e after 2100 LT. Using the data from ground based GPS and ionosonde measurements, Li et al. [22] have reported that during the June solstice of the solar minimum years, generally most of the EPBs are generated at post-midnight sector. However these EPB are predominantly initiated around the midnight from gravity wave perturbation and survive for several hours until the sunrise/daytime. The post-midnight irregularities are found to be more frequent during the solar minimum year than that during solar maximum condition and their occurrence are found to be maximum during June solstice. The development of post sunset spread-F/plasma bubble irregularity are governed by evening F-layer drift and the role of precursor gravity waves in seeding the instability, by perturbations in density and polarization electric fields, is well understood for post sunset spread-F based on case studies and statistical analysis [2]. During low solar activity, the PRE is weaker and the role of precursor gravity waves in spread-F development is clearly observable. Furthermore, during the solar minimum, when the gravity wave forcing gains dominance relative to PRE for instability growth, the spread F onset is generally delayed and occurred in midnight/post-midnight sector. At low latitude sites, post-midnight spread-F have similar characteristics to mid latitude spread F which is supposed to be produced by medium-scale traveling ionospheric disturbances(MSTIDs) [2, 23]. The MSTIDs are primary disturbances in the mid-latitude ionosphere which modulate ionospheric plasma and even generate irregularities (Spread-F).

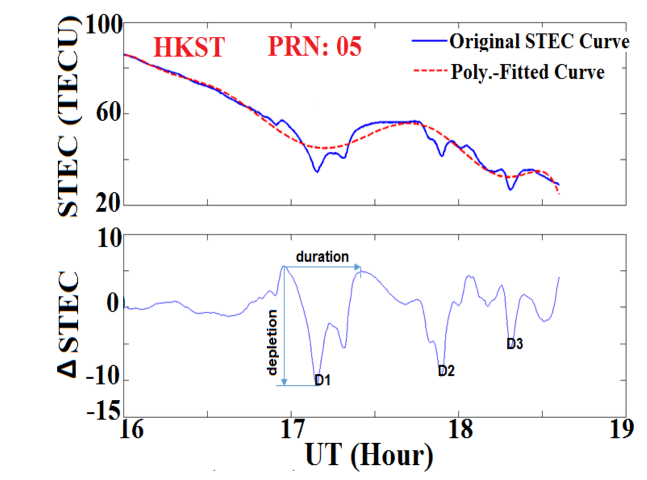

Figure 2: Time series of original STEC and best polynomial fitted curve observed by PRN 05 at HKST station, Hong Kong during quiet day on June 27, 2007 (b) the time series of de-trended of STEC (ΔSTEC) showing characteristics of the Plasma bubble. D1, D2, D3 represents depth of three successive plasma bubbles observed by PRN 5.

Unlike the nighttime occurrence of plasma bubble, the daytime occurrence also happens but such cases are very rare. It is known from earlier studies that the daytime scintillation is possibly caused by the sporadic E layers (Es) associated irregularities [24-25] however their association with plasma bubbles is not known. The statistical analysis of EPB made by earlier researchers have shown the occurrence probabilities of plasma bubbles has peaks at night but does not become zero until 1000 LT in the morning sector [26]. Li et al. [22] found that ionospheric irregularities occurred at mid-latitudes in the post-mid night sector and suggested that the irregularities might be related to equatorial plasma bubbles near sunrise. Using the data from C/NOFS satellite, recently Huang et al. [27] reported that the occurrence of long-lasting daytime EPB of ~ 12 h from post-mid night to mid- afternoon. They further argued that the higher altitude ~ 800 km or higher attained by the plasma bubble to be a responsible factor for its existence for a longer duration ~12 h till mid-afternoon. Because at higher altitude the photo-ionization takes longer time to fill the daytime plasma bubbles than that at the lower altitude.

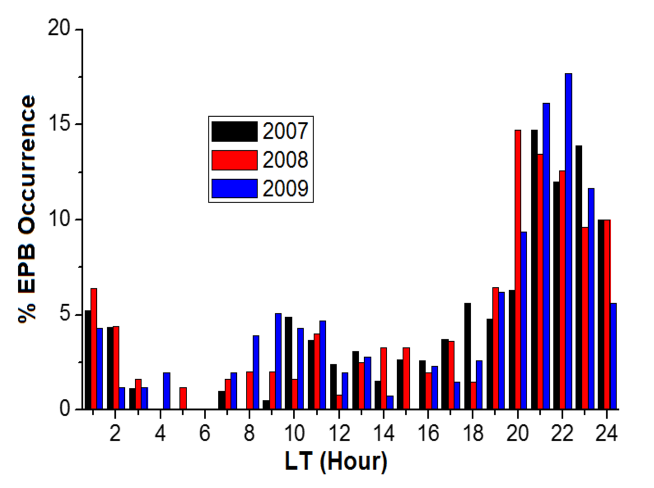

Figure 3: EPB occurrence (%) against local time hour during each year from 2007 to 2009

To study the seasonal EPB occurrence, the monthly occurrences have been grouped into four seasons namely March-equinox (February to April), June-solstice (May to July), September-equinox (August to October) and December-solstice (November to January). The seasonal EPB occurrence for each year during deep solar minimum 2007-2009 is shown in Figure (4). It is clearly evident from figure (4) that EPB occurrences are found to be a maximum during the June solstice for the deep solar minimum 2007-2009 which in contrast to the fact of general EPB occurrences which is expected to be maximum during the equinox season. Although the theory proposed by Tsunda [5] is failed to explain this unusual seasonal EPB occurrence but our results are found in agreement with those reported by Liu et al. [28]. Using GPS data, Liu et al. [28] conducted the analysis of ionospheric scintillations over Sanya region and reported two clear seasonal maxima in scintillation (S4) and significant TEC fluctuation (ROTI), corresponding to the spring (March–April) and autumn (September–October) equinoctial months only except during the solar minimum years 2008–2009. Moreover during 2008-2009, they have reported scintillation maxima during the June.

The latitudinal and longitudinal dimension of plasma bubbles expressed in km is computed during 2007-2009. Figure 5 shows the percentage distribution of size in latitude and longitude expressed in km of all observed plasma bubble during each year from 2007-2009. As seen from this figure,

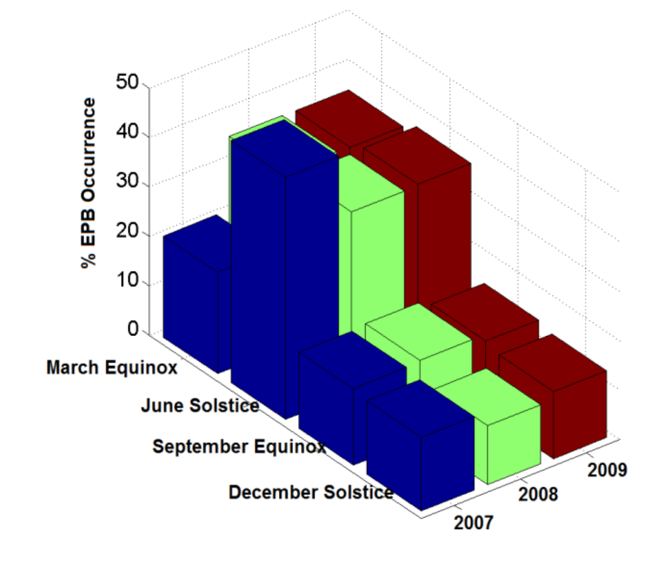

Figure 4: Percentage occurrence of seasonal EPB during 2007-2009. The seasonal EPB for each year is computed with reference to total number of EPB observed for respective year.

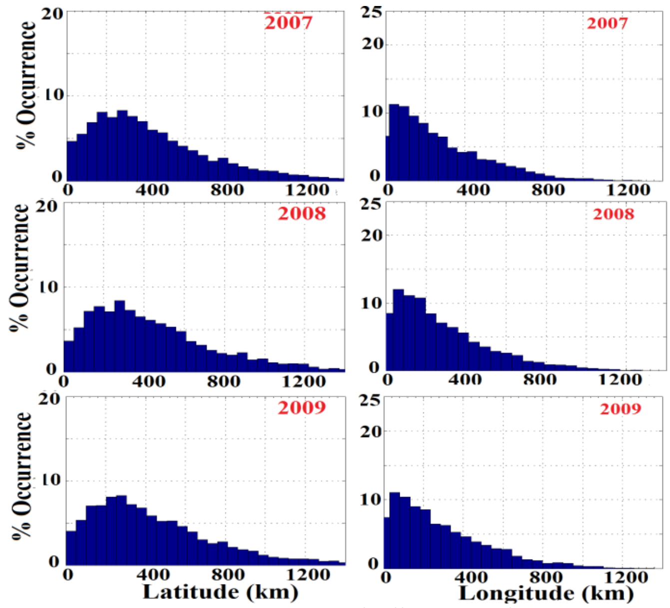

Figure 5: Percentage (%) distribution of different size of EPB in latitude (left panel) and in longitude (right panel) expressed in km observed from 2007-2009.

the plasma bubble occurrence is more probable with latitude size 200-400 km. The longitudinal size of the majority of plasma bubble exists for less than 200 km.

IV. CONCLUSION

The occurrence and characteristics of plasma bubbles during deep solar minimum during from 2007 to 2009 have been studied using STEC data from the SatRef GPS CORS network in Hong Kong. The occurrences of plasma bubbles show unusual seasonal features. During deep solar minimum 2007-2009 the EPB occurrence is found to be maximum during June solstice i.e higher than both the equinox. The high occurrence of EPB during June solstice of deep solar minimum 2007-2009, which has been observed over Hong Kong using local GPS CORS network, is an unusual and significant finding of this study which could not be explained on the basis of the theory proposed by Tsunda [5]. Although these exceptional features are not fully explained but one possible cause could be a very low ambient plasma density during 2007-2009 as reported by Huang et al. [16]. The seasonal EPB occurrences clearly show the equinoctial asymmetry in EPB occurrences which has been observed throughout 2007-2009.

TABLE I.

Station Code	Geographic Latitude	Geographic Longitude	Geomagnetic Latitude
HKKT	22º, 26' N	114º ,03' E	12º, 40' N
HKFN	22º, 29' N	114º ,08' E	12º, 43' N
HKLT	22º, 25' N	113º ,59' E	12º, 39' N
HKMW	22º, 15' N	114º ,00' E	12º, 29' N
HKNP	22º, 14' N	113º ,53' E	12º, 28' N
HKOH	22º, 14' N	114º ,13' E	12º, 29' N
HKPC	22º, 17' N	114º ,02' E	12º, 31' N
HKSC	22º, 19' N	114º ,08' E	12º, 33' N
HKSL	22º, 22' N	113º ,55' E	12º, 54' N
HKSS	22º, 25' N	114º ,16' E	12º, 41' N
HKST	22º, 23' N	114º ,18' E	12º, 38' N
HKWS	22º, 26' N	114º ,20' E	12º, 40' N

TableI: List of GPS stations in Hong Kong with their geographic and geomagnetic coordinates.

Generally EPB occurrence is found to be maximum during the nighttime hours (1900-2400) than that during daytime. The daytime occurrences of EPB are also observed but their abundances are very small as compared to nighttime. Although the daytime EPB generation are not fully explained but EPB generated in post-mid night sector can survive until the daytime hour [27]. The EPB occurrences during 2007-2009 of 200-400 km dimension in latitude are found to be more probable whereas the same are more probable in the longitude dimension less than 200 km.

ACKNOWLEDGEMENT

The Lands Department of the Government of Hong Kong Special Administrative Region (HKSAR) is acknowledged for providing the GPS data from the Hong Kong Satellite Positioning Reference Station Network (SatRef) (http://www.geodetic.gov.hk/smo/welcome.htm). We also are thankful for world data center at Kyoto University, Japan, for providing geomagnetic data (http://wdc.kugi.kyoto-u.ac.jp/) and for NOAA for providing the solar data (http://www.ngdc.noaa.gov). The supports from the Hong Kong Research Grants Council (RGC) Early Career Scheme (ECS) Fund (Project No. PolyU 5325/12E (F-PP0F)) and the National Natural Science Foundation of China (No. 41274039) are gratefully acknowledged.

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