

Equatorial Plasma Bubble Velocity Estimation over Southeast Asia

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Abstract

A method to estimate the drift velocity and direction of equatorial plasma bubbles (EPB) is presented. The method employs the dynamic time warping (DTW) algorithm on global navigation satellite system (GNSS) data collected by nine closely spaced receivers of the Singapore satellite positioning reference network (SiReNT). EPB drift velocity field maps are computed from detrended slant total electron content (STEC) measurements, and an uncertainty analysis is combined with a directional filtering to ensure reliability. The estimated drift velocities range from 40 m/s to 200 m/s, which is consistent with typical values found in the Southeast Asia region.

1 Introduction

Research on equatorial plasma bubbles (EPBs) using global navigation satellite system (GNSS) measurements has gained substantial momentum over the past few decades [1, 2]. EPB evolution can be described as a non-linear process driven by the Rayleigh-Taylor instability [3], with EPB structures aligning along local geomagnetic field lines. EPBs are commonly identified as depletions in total electron content (TEC), commonly derived from dual-frequency GNSS measurements [4].

Recently, EPB detection in the Southeast Asia region has been facilitated by the deployment of a dense GNSS network [5]. Short-term prediction models, that combine GNSS and ionosonde data via deep learning, have shown promising accuracy [6]. However, estimating EPB drift velocity remains challenging. Prior approaches have used correlation analysis across receiver networks with triangulation strategies [7, 8].

Here, a novel EPB drift velocity estimation technique is implemented based on dynamic time warping (DTW). DTW has been popularized by the work of [9], and has gained traction across various applications, particularly in speech recognition and seismic data processing [10, 11]. DTW is adapted to identify EPB structures using detrended slant total electron content (STEC) data collected by closely spaced GNSS receivers of the Singapore Satellite positioning reference network (SiReNT) from the Singapore Land Authority (SLA) [12]. This network comprises nine strategically positioned receiver stations spread across Singa-

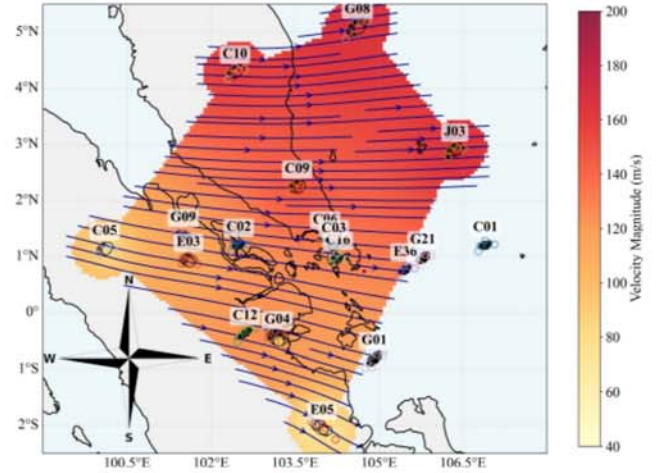


Figure 1. Example of EPB drift velocity field map showing interpolated velocity (m/s) and streamlines using dynamic time-warping applied to STEC measurements from the SiReNT receiver network on 12 October 2022 at 22:59:40 (Singapore time, SGT, 8 hours ahead of UTC).

pore. The receiver stations are designated, from west to east, as SSTS, SNYU, SSMK, SNUS, SRPT, SNPT, SMS1, SNSC, and SLYG. Each station continuously receives data from satellites from the GPS, GLONASS, Galileo, BeiDou, and QZSS constellations. This enables computation of temporally resolved EPB drift-velocity field maps covering the Southeast Asian longitudinal sector, as discussed below. Fig. 1 shows an example of a computed EPB velocity map, with the drift velocity estimation ranging from 40 to 200 m/s with an eastward moving direction.

2 Methodology

2.1 EPB Drift Velocity Estimation

EPB drift velocity is estimated from signal delays between different receiver stations receiving the same GNSS satellite signal, assuming a constant speed in a plane. In Fig. 2, STEC measurements from two receivers monitoring satellite C03 on the night of 12 October 2022 are shown, with the SNYU station shown in blue and the SLYG station in red. The grey dotted lines denote 100 instances of the time offsets obtained using DTW. The delays follow the west-east longitudinal station disposition, enabling velocity es-

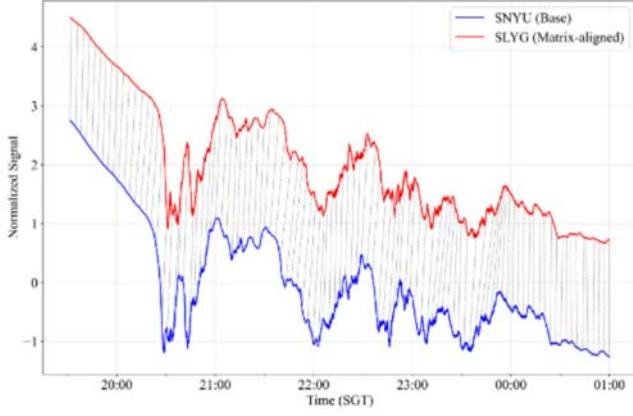


Figure 2. Example of DTW alignment of STEC measurements obtained from BeiDOU satellite C03 data received by SiReNT stations SNYU and SLYG.

timation from these delays and the difference in the associated ionospheric pierce points (IPP). Data from $N = 9$ receiver stations is available. A subset $k \geq 3$ is chosen to maximize $\binom{N}{k}$ combinations from the N available stations, while maintaining robust speed evaluation. Arrival delays are modelled as:

$$t(x, y) = \beta_x x + \beta_y y, \quad (1)$$

where (x, y) are the station positions relative to the origin, with x and y representing the west-east and south-north directions, respectively. The coefficient vector $\beta = [\beta_x, \beta_y]^T$ is obtained via least-squares regression:

$$\beta = (\mathbf{A}^T \mathbf{A})^{-1} \mathbf{A}^T \mathbf{b}, \quad (2)$$

where $\mathbf{A}$ contains station north-south and east-west differences w.r.t. the origin and $\mathbf{b}$ contains arrival delays w.r.t. the origin. Assuming a planar wavefront, the velocity vector relates to the gradient of the arrival time as:

$$\mathbf{V} = \frac{\nabla t}{\|\nabla t\|_2} = \frac{[\beta_x, \beta_y]^T}{\sqrt{\beta_x^2 + \beta_y^2}}. \quad (3)$$

Finally, propagation speed v and direction θ are computed from:

$$v = \|\mathbf{V}\|_2 = \frac{1}{\sqrt{\beta_x^2 + \beta_y^2}}, \quad \theta = \text{atan2}(\beta_y, \beta_x). \quad (4)$$

2.2 Dynamic Time Warping

The estimation of the EPB velocity requires both determining signal delays between GNSS received signals and the positions of the GNSS receivers, the satellites, and the associated IPPs at 350 km. Signals may exhibit local stretching or compression, which precludes the use of cross-correlation. Local temporal variations can therefore be captured using the DTW algorithm.

The first step consists of computing the alignment cost matrix, where each entry is the 1-norm distance between the

samples, labelled by the indices i and j , extracted from both signals $\mathbf{f}$ and $\mathbf{g}$ of length $N_t + 1$:

$$e(i, j) = |f(i) - g(j)|, \quad \forall (i, j) \in \{0, 1, \dots, N_t\}^2. \quad (5)$$

Many variants have been introduced in the literature (e.g., [13]), where the distance is computed on a descriptor at each sample rather than directly on the raw signal. Once the error is obtained, it is recursively accumulated to calculate the path p of minimum error among all paths P :

$$\min_{p \in P} \sum_{(i, j) \in p} e(i, j). \quad (6)$$

The optimal warping path is recovered by backtracking from the end to the beginning, subject to the usual monotonicity and continuity constraints. Different accumulating and backtracking strategies and path constraints are explored in the literature. Here, the approach of [11] is followed.

DTW allows computations of the shifts between two signals from two receivers. However, many receivers have access to the same signals and it is possible to combine them into a minimization problem [11]. The optimization problem aims at finding the shifts s that satisfy:

$$t_i + s(t_i) = t_j + s(t_j) \iff t_i - t_j = s(t_j) - s(t_i). \quad (7)$$

This problem translates into computing the shifts s that minimize the following system:

$$\min_s \|\mathbf{D}_s \mathbf{s} - \mathbf{d}_t\|^2, \quad (8)$$

where $\mathbf{D}_s$ and $\mathbf{d}_t$ refer to the sparse matrix operator, consisting of the values 1 and -1 at the corresponding shift differences, and the time shift matrix, respectively. This sparse system of linear equations can be solved efficiently using the iterative conjugate gradient solver (CGS) method.

2.3 Uncertainty Analysis and Filtering

DTW aligns points in time of two signals and yields local time shifts. These shifts are physically meaningful only where STEC exhibits EPB-related variations. Elsewhere, the warping simply reflects mathematical alignment with no geophysical significance. Therefore, shifts from segments without STEC variability must be filtered out when constructing the velocity map.

If a quantity depends on several independent measured variables and can be expressed as a differentiable function, the effect of measurement uncertainties on that quantity can be evaluated using partial derivatives. Here, $U(\cdot)$ denotes the worst-case measurement uncertainty in the corresponding variable, e.g., $U(\Delta x)$ for uncertainty in displacement and $U(\Delta t)$ for the time interval. For velocity $v = \Delta x / \Delta t$, the associated worst-case relative uncertainty is the linear combination of both time shifts and position relative uncertainties. Moreover, since the positions of the receiver and satellite

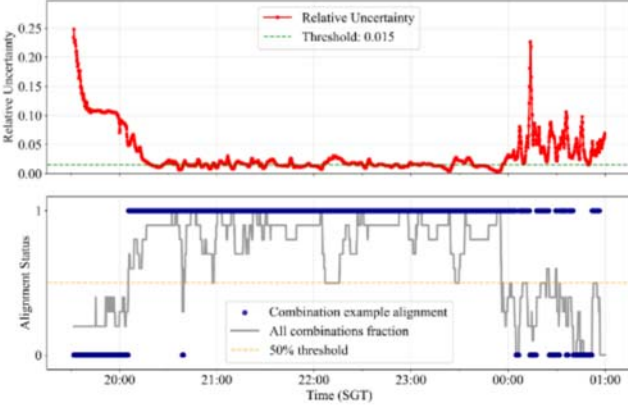


Figure 3. Example of filtering of data from satellite C03. (Top) Relative uncertainty with 1.5% threshold. (Bottom) $E \times B$ drift direction validation filter with station combination example SNPT-SNYU-SRPT. A value of 1 represents drift alignment with $E \times B$ and 0 means non-aligned.

are accurately known, the IPP localization is highly accurate as well with regards to the path lengths. Therefore, the uncertainty in positions becomes negligible and the relative velocity uncertainty simplifies to:

$$\frac{U(v)}{v} = \frac{U(\Delta x)}{\Delta x} + \frac{U(\Delta t)}{\Delta t} \approx \frac{U(\Delta t)}{\Delta t}. \quad (9)$$

Two filtering methods are applied to ensure reliable velocity estimation. First, when DTW identifies delays near zero, indicating minimal ionospheric perturbation, unrealistically high velocities result from the inverse relationship in (4). A relative uncertainty threshold of $U(v)/v = 1.5\%$ filters out these physically implausible estimates from undisturbed conditions. For $U(\Delta t) = 2$ s, only events for which $\Delta t \geq 133$ s are considered in the velocity computation.

Second, DTW can introduce artificial delays through unnecessary time series stretching and squeezing that do not correspond to actual ionospheric disturbances. To address this, directional validation compares the estimated propagation direction with the theoretical $E \times B$ drift direction calculated from the IGRF model [14]:

$$\hat{\mathbf{d}}_{E \times B} = \frac{[B_n - B_e]^T}{\sqrt{B_n^2 + B_e^2}}, \quad (10)$$

where B_n and B_e are magnetic field components at 350 km altitude. Velocity estimations for a satellite are considered valid only when the alignment angles for more than 50% of the combinations passes the filter on alignment angle $\theta_{align} = \arccos(\hat{\mathbf{V}} \cdot \hat{\mathbf{d}}_{E \times B}) \leq 45^\circ$. This ensures physical consistency with expected plasma drift mechanisms.

3 Results

SiReNT data for several years was purchased from SLA and EPB velocity maps were computed using the above

method. EPB velocity fields over Southeast Asia are expressed as maps that encode their spatial structure and temporal evolution. Fig. 1 and 4 present two examples of velocity field maps computed for 12 October 2022, selected as a representative case study. This date was chosen because EPBs are clearly visible while geomagnetic conditions remain quiet, with a maximum planetary index K_p of 2+, ensuring that the observed velocity patterns reflect natural EPB dynamics without external magnetic disturbances.

The maps present EPB drift velocity estimates derived from DTW-aligned STEC measurements across the receiver network, showing interpolated and extrapolated velocities via the colormap and directions as streamlines at 350 km IPPs. Quality control is implemented through uncertainty filtering, which removes satellite combinations with irrelevant DTW alignments, and $E \times B$ drift validation, which ensures physical consistency by filtering out velocities misaligned with the theoretical plasma drift direction by more than 45° . An example of DTW alignment filtering associated to Fig. 2 is depicted in Fig. 3. Firstly, pre- and post-EPB signals are successfully filtered with the relative uncertainty threshold. Intermediate values, corresponding to small time shifts, are also discarded. Secondly, valid EPB signals show a strong magnetic collinearity, and peripheral estimations are well removed. Finally, an additional rate of TEC index (ROTI) analysis has been conducted in the form of a Neyman-Pearson test to ensure EPB presence and remove satellites without EPB signatures.

The velocity field maps reveal several key characteristics of EPB propagation dynamics in the Southeast Asian region. Fig. 1 presents the velocity field map at 22:59:40 local time, approximately three hours after the initial EPB onset. At this stage, half the satellites satisfy the filtering criteria and satellites in the southeastern and central regions are excluded. The velocity field shows significant spatial variation, with velocities ranging from 60 m/s in the southern and western regions to 170 m/s in the northern and eastern areas. A gradually increasing velocity between these regions is noted for satellite C09 with speeds averaging 150 m/s. The dominant propagation pattern is eastward with a slight southward component, consistent with the expected $E \times B$ drift direction in the post-sunset ionosphere. Data from satellite G08 exhibits eastward propagation with a slight northward deflection, indicating spatial variability in the velocity meridional component.

Four satellites with IPPs located in the southeastern portion of the observation area are filtered out due to exceeding uncertainty thresholds. Analysis reveals that this filtering occurs because EPB activity is weak in this eastern region at the observed time.

Fig. 4 shows results for 19:56 SGT, i.e., three hours before the results of Fig. 1. EPB velocities emerge predominantly near the sunset terminator at 350 km altitude, confirming that the selected satellites meet the filtering criteria

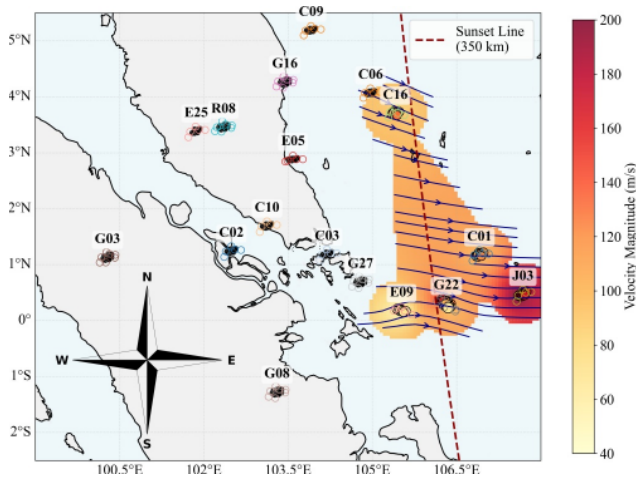


Figure 4. EPB velocity field map on 12 October 2022 at 19:56 Singapore time. The red dotted line is the solar terminator at 350 km height.

for measurement uncertainty, directional consistency, and ROTI thresholds. The spatial distribution shows notable velocity variations across different satellite tracks. Lower velocities of 70 m/s to 100 m/s are observed for satellites C16 and E09, respectively. This is attributed to their IPPs being located ahead of the advancing solar terminator, where EPB initiation conditions have not yet been established. In contrast, data from satellites C01 and J03 exhibit significantly higher velocities ranging from 120–160 m/s, indicating active EPB development in regions where post-sunset conditions favour plasma instability growth. This velocity gradient demonstrates the close temporal and spatial relationship between the solar terminator passage and EPB onset, with maximum propagation speeds occurring in the immediate post-sunset ionospheric environment. J03 velocities may have been enhanced by DTW squeezing effects.

4 Conclusion

A novel method for the computation of EPB drift velocity maps over Southeast Asia is introduced and applied to data from a network of GNSS receivers in Singapore and STEC-derived signals. Time shifts are derived from dynamic time warping alignments, posed as a minimization problem. The method is further refined with a two-step filtering procedure on both speed uncertainty and magnetic field collinearity. The method is demonstrated using data from 12 October 2022, when EPB activity was present over Southeast Asia. The observed velocities fall within realistic event ranges (40–200 m/s).

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