On the sources of day-to-day variability in the occurrence of equatorial plasma bubbles: An analysis using the TIEGCM

Brett A. Carter

SPACE Research Centre, RMIT University, Australia, www.rmit.edu.au/space
Institute for Scientific Research, Boston College, USA, http://www.bc.edu/research/isr/
Outline

• Introduction:
  – Equatorial Plasma Bubbles (EPBs) / Equatorial F-region Irregularities (EFIs)
  – EPB/EFI climatology using COSMIC Radio Occultation scintillation data
  – Potential sources of day-to-day variability

• Instrumentation

• Post-sunset EPB observations from Vanimo:
  – Climatological variability of EPB occurrence
  – Superposed Epoch Analysis (SEA) of geomagnetic and ionosonde data
  – Thermosphere-ionosphere model analysis

• Discussion and interpretation

• Summary and conclusions
Equatorial Plasma Bubbles

Equatorial Spread F (ESF)/Equatorial F-region

Projection to Magnetic Equator

Magnetic Field Lines (red)

Airglow Emission Plane

Kelley et al. (2006)

Generalised Rayleigh-Taylor instability

$$\gamma = \frac{\Sigma^F_P}{\Sigma^E_P + \Sigma^F_P} \left( V_p - U^P_n - \frac{g_L}{v_{in}^{eff}} \right)$$

(Gentile et al., 2006)

Equatorial Plasma bubbles

Huang et al., 2012

Upward plasma drift - prereversal enhancement after sunset

http://center.stelab.nagoya-u.ac.jp/site1/info_e/kagoshima.html

GPS TEC ROTI Map 10:30UT 06 Apr 2011
The Low Earth Orbit (LEO) satellites measure the GPS signals that are occulted by the Earth’s atmosphere. These occulted signals are used to infer atmospheric properties, such as wet temperature (troposphere) and electron density (ionosphere).

**Dataset:** ~ 5 years (2007-2011) of RO data collected by the COSMIC satellites.

The ‘s4max9s’ is used for each event instead of the ‘s4max’ parameter to avoid the use of spurious S4 measurements.
Sorting the data according to season and longitude sector show strong differences in EFI occurrence.

These trends match those found in previous studies of EPB occurrence; e.g. Burke et al. (2004)

Occurrence of F-region irregularities is strongly controlled by the magnitude of the angle between the magnetic field and the direction of the day-night terminator (Tsunoda, 1985)
The strength of the pre-reversal enhancement has been a good candidate for the daily EPB variability:

- Highly variable during quiet times
- Strongly influenced by changes in storm and substorm activity (via under-shielding and over-shielding electric fields)
- Has been shown as a good parameter to feed into EPB prediction models (e.g. Retterer)
Another candidate is the abundance of ‘seeding’ waves to kick off the instability:

$$P_{ESF} = P_S \cdot P_i,$$

where $P_S$ is the seeding probability and $P_i$ is the instability probability.

- Atmospheric gravity waves from convective storms in the troposphere (e.g. Tsunoda, 2010)

- Large-scale wave structure caused by the collisional shear instability in the bottomside F layer (Tsunoda and Ecklund, 2007)
Vanimo Ionospheric Scintillation Observations

Vanimo:
- Ionosonde – vertical incidence sounding radar

Important parameters:
- peak plasma frequency (density)
- layer altitude

(a) Normal conditions
(b) Equatorial Spread F event
Vanimo Ionospheric Scintillation Observations

Vanimo:
- Ionosonde – vertical incidence sounding radar
- GPS Ionospheric Scintillation Monitor (ISM)

ISM data:
- Amplitude scintillation index, S4

Occurrence of post-sunset (after ~10 UT) scintillation events is mostly largest during equinox and smallest during solstices.

Burke et al. (2004)
Observations: 2000 March equinox

The EPB climatology observed matches that in previous works.
The day-to-day EPB occurrence variability is the problem we wish to address in the Asian longitude sector.
Is there a simple and reliable way of predicting the onset of EPBs hours beforehand?
There is no simple and clear correlation with solar or geomagnetic activity.

Can nearby ionosonde data provide insights into some of the key fluxtube-integrated parameters within the R-T growth rate??

\[
y = \left( \frac{\sum_{p} F}{\sum_{p} E + \sum_{p} F} \right) \left( V_p - U_{n,p} - \frac{g_L}{V_{in}} \right) \frac{1}{L_n} R_T
\]
Superposed epoch analysis

Scintillation event selection criterion:
mean(S4) + stddev(S4) ≥ 0.3

Conduct separate Superposed Epoch Analyses (SEA) on the data for days with, and without, EPB detections.

EPB detections were also compared with ionosonde Equatorial Spread F (ESF) detections (vast majority of ESF detections coincident with EPB detections).

Institute for Scientific Research / B. A. Carter
The EPB event selection criterion clearly separates the non-EPB days from the EPB days.

Geomagnetic activity differences greater than $\sigma$ and non-EPB days.

Both $h^{'}F$ and $\Delta h^{'}F/\Delta t$ show deviations on EPB days.

The Es and F layer peak plasma frequency data largely do not show differences greater than $1\sigma$.

Do these results hold for other equinoctial months?
SEA results: Sept equinox 2000

Deviations in \( h'F \) and \( \Delta h'F/\Delta t \) are also observed during Aug-Oct 2000.

These results are equinoctial periods maximum (e.g. 2001, 2002).

The Vanimo ionosonde detecting the pre-reversal enhancement (PRE) in the F layer close to sunset, and altitude of the F layer equatorial location (~10° S MLAT).

Are these results replicated from ionosphere-thermosphere modelling?
The Thermosphere Ionosphere Electrodynamics General Circulation Model (TIEGCM) is a time-dependent 3D physics-based (i.e. not empirical) numerical simulation of the Earth’s thermosphere and ionosphere.

**Inputs:**
- Solar activity (F10.7 cm flux)
- Geomagnetic activity (Kp index)

**Outputs:**
- Electron density
- F layer height
- 3D plasma drift
- Thermospheric density
- 3D neutral winds…
- …
- Basically, everything that we need…
TIEGCM output agree rather well with ionosonde data; in particular, Vz increase prior to EPBs.

H’F doesn’t show the same feature as in the ionosonde data.

Interestingly, the TIEGCM shows lower F-region peak plasma densities around 10 UT on EPB days compared to non-EPB days.

The modelled E region shows very little variability.

How meaningful is the day-to-day variability exhibited in the TIEGCM outputs…?
The TIEGCM was used to calculate the R-T growth rate each hour:

$$\gamma = \frac{\Sigma_p^F}{\Sigma_p^F + \Sigma_p^E} \left( V_p - U_n^P \right) \cdot \frac{g_L}{\nu_{in}^{eff}} \cdot \frac{1}{L_n} - R_T$$

The R-T growth rate (calculated purely from TIEGCM output) is 1σ higher on EPBs compared to non-EPB days.

A breakdown of the terms gives a clear indication which parameters are exhibiting the observed daily variability in the GPS data.

The gravity term is causing higher growth rates on EPB days.
Can the TIEGCM be used to predict EPBs?

- Daily maximum average $S_4$ shows good correlation with TIEGCM growth rate
- Gravity term shows good correlation with R-T growth rate, particularly in terms of the maxima and minima

**Prediction stats:**

<table>
<thead>
<tr>
<th>Predicted</th>
<th>EPBs</th>
<th>Yes</th>
<th>No</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yes</td>
<td>17</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>No</td>
<td>5</td>
<td>31</td>
<td></td>
</tr>
</tbody>
</table>

- Heideke skill score = 0.529
- Accuracy $(17+31)/56 = 85.7\%$

- Flux-tube integrated ion-neutral collision frequencies tend to spike on non-EPB days
TIEGCM: EPB prediction?

\[
\gamma = \frac{\Sigma_P^F}{\Sigma_P^F + \Sigma_P^F} \left( V_p - U_n^P - \frac{g_L}{v_{in}^{eff}} \right) \frac{1}{L_n} - R_T
\]

The ion-neutral collision frequency is calculated as follows;

\[
\nu_{in}^{eff} = \frac{1}{N_e} \int n_e \sum_{s=1}^{6} \nu_s dS
\]

Note the electron density weighting, which weighs the collision frequencies higher at higher electron density locations along the flux tube.

Therefore, daily changes in the electron density distribution and the thermospheric density along the flux tube result in changes in the R-T growth rate.
The altitude-latitude distributions show that the location/altitude of the plasma, relative to the thermospheric density levels, is important in the control of the gravity term in the growth rate.

(a) $n_e$
(b) $\log_e(N_2)$
(c) $n_e*N_2$
Summary and conclusions

The statistical occurrence climatology of GPS scintillation events detected by the Vanimo ISM agreed well with the EPB occurrence climatology in the Asian region.

- The occurrence of EPBs was correlated with times of the year when the angle between the magnetic field and the day-night terminator was small.

Separate superposed epoch analyses were conducted for EPB and non-EPB days:

- Geomagnetic activity and solar wind data showed no clear control of the day-to-day EPB occurrence detected by the Vanimo ISM.
- The Vanimo ionosonde data showed that the $h'F$ and the upward velocity of the F layer were $\sim 1\sigma$ larger on EPB days versus non-EPB days.

The TIEGCM results agreed well with the ionosonde data and was then successfully used in the prediction of EPBs on a day-to-day basis with 85% accuracy:

- The upward plasma drift and the ion-neutral collision frequency (via daily changes in the electron density and thermospheric distributions) were found to be controlling the daily variability in EPB occurrence.
- From the TIEGCM analysis, it can also be concluded that other previously investigated sources of daily EPB variability (e.g. atmospheric gravity waves and thermospheric winds) were not found to control the daily occurrence of post-sunset EPBs in this period.