Three-dimensional high-resolution plasma bubble modeling

Tatsuhiro Yokoyama, Hiroyuki Shinagawa, and Hidekatsu Jin

National Institute of Information and Communications Technology, Japan
Spread F – an old equatorial aeronomy problem finally resolved?

R. F. Woodman
Radio Observatorio de Jicamarca, Instituto Geofísico del Perú, Lima, Peru

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Abstract. One of the oldest scientific topics in Equatorial Aeronomy is related to Spread-F. It includes all our efforts to understand the physical mechanisms responsible for the existence of ionospheric F-region irregularities, the spread of the traces in a night-time equatorial ionogram – hence its name – and all other manifestations of the same. It was observed for the first time as an abnormal ionogram in Huancayo, about 70 years ago. But only recently are we coming to understand the physical mechanisms responsible for its occurrence and its capricious day to day variability. Several ad-
Scintillation

- Fresnel diffraction
  \[ \sqrt{2}D_F = \sqrt{2}\lambda z \approx 400\text{m} \]
- Serious problem for communication and navigation.
Woodman and LaHoz (1976)

- 99% density depletion causes severe scintillation.

Kelley et al. (1981)

Otsuka et al. (2002)
NICT’s SEALION Observatories
Numerical Modeling of Plasma Bubbles

- What we have not known:
  - Day-to-day variability
  - Precursor

- We need to understand:
  - Background conditions to drive plasma bubble
  - Initial seeding at the bottomside F region

- Various observations (radars, optical imagers, rockets, satellites) have been conducted, but not answered yet (for more than 70 years!)

- We are developing a new high-resolution model and integrating it to a global ionosphere model.
Plasma density is solved from (1).

Polarization electrostatic potential is solved from (2)-(4).
Other Models

Zalesak et al. (1982)

Aveiro et al. (2012)

Huba et al. (2008)

Retterer (2010)
Numerical Model for Plasma Bubble

- Dipole orthogonal coordinate
- Longitudinal coverage is 3.4° with 0.01° resolution (~1km).
- O⁺ (F region), NO⁺ (E region), Fe⁺ (Es layer [not yet])
Initial Condition

- Apply sinusoidal perturbation by lifting the density profile to mimic LSWS.
Results (no neutral wind)

Yokoyama et al. (2014)
Vertical/Horizontal Density Distribution

Yokoyama et al. (2014)
Eastward Propagation by Neutral Wind

- Eastward E field turns to be westward after 1800 s.
- Eastward neutral wind produces dynamo electric field to move the bubble eastward.
LSWS at the Bottomside, Plumes at the Topside

Tsunoda et al. (1982)
Western Wall Unstable
Whole Atmosphere-Ionosphere Coupled Model

- Ground-to-topside model of Atmosphere and Ionosphere for Aeronomy (GAIA) model
- Coupling with the high-resolution bubble model enables us to understand the day-to-day variability of plasma bubbles.
• A new three-dimensional high-resolution numerical model to study equatorial plasma bubble (EPB) has been developed with a spatial resolution of as fine as 1 km.

• Turbulent plume-like irregularities can be spontaneously generated only from large-scale perturbation at the bottomside.

• Western wall is more unstable than eastern wall.

  Future work: Collaboration with a global model (GAIA) for background initial conditions (n, E, U, etc.)
The lower E region consists of magnetized electrons and unmagnetized ions. → Complicated electrodynamics!
Linear Growth Rate of Rayleigh-Taylor Instability

\[ \gamma_L = \frac{1}{n_0} \frac{\partial n_0}{\partial z} \left( \frac{E}{B} - \frac{g}{v_{\text{in}}} \right) - \beta_L \]

Local

\[ \gamma_{FT} = \frac{\sum_P^F}{\sum_P^E + \sum_P^F} \left( \frac{E}{B} - \frac{g_e}{v_{\text{eff}}} \right) \ldots \]

Flux-tube integrated
Large-Scale Wave Structure (LSWS)

Tsunoda et al. (1982)

Tsunoda and White (1981)

Tsunoda et al. (1982)
• Equipotential contours can be regarded as streamlines of plasma in the F region.
• The top of the bubble becomes flat, where the bifurcation occurs.
After bifurcation, high density region between the two bubbles moves downward due to westward polarization electric field, then pinch off the west bubble.
Secondary instability occurs along the bubble wall, whereas pinched-off bubble stops growing.
Dependence on Zonal Resolution

1km

2km

3km

4km

5km
Dependence on Zonal Resolution

1km

3km

5km
- Topside structure depends on the grid sizes.
- Bottomside structure and vertical velocity is similar.