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主　論　文　の　要　旨

論文題目　Statistical Study of Equatorial Plasma Bubbles in Southeast Asia Using Ionosondes, GPS, and Equatorial Atmosphere Radar
(イオノゾンデ、GPS 及び赤道大気レーダーを用いた東南アジアにおける赤道プラズマバブルの統計的研究)

氏　　名　　Prayitno　Abadi

論　文　内　容　の　要　旨

Equatorial plasma bubbles (EPBs) are a phenomenon that refers to plasma depletion in the *F*-region in the equatorial and low-latitude ionosphere. Studies of EPBs have become important because the irregularities (plasma density fluctuations) embedded in EPBs could degrade the signal of a trans-ionospheric radio wave, such as causing scintillation on the GPS signal. The Rayleigh-Taylor instability (RTI) is considered a fundamental theory for EPB generation. However, several questions related to the EPB phenomenology arise, such as what are the factors that control the morphology of the EPB and cause multiple EPB generation? These questions are addressed in this thesis.
This thesis consists of three studies that aim to investigate the generation and morphology of EPBs in Southeast Asia during the equinoctial months. We employed radio instrumentation to probe the ionosphere. Details of the instrumentation used in these studies are described as follows: (1) ionosondes were installed at Chumphon (CPN; 10.7°N, 99.4°E; magnetic latitude: 3.0°N) in Thailand and at Bac Lieu (BCL; 9.3°N, 105.7°E; magnetic latitude: 1.5°N) in Vietnam, (2) ground GPS receivers were deployed at Kototabang (KTB, 0.2°S, 100.3°E; magnetic latitude: 10.4°S), Pontianak (PTK; 0.0°S, 109.3°E; magnetic latitude: 9.8°S), and Bandung (BDG; 6.9°S, 107.6°E; magnetic latitude: 16.7°S) in Indonesia, and (3) 47 MHz Equatorial Atmosphere Radar

(EAR) was used at KTB. We also analyzed the zonal thermospheric wind data derived from in situ measurements of the accelerometers onboard the Challenging Minisatellite Payload (CHAMP) (orbit: meridional direction, the altitude of ~400 km) and the Gravity Field and Steady-State Ocean Circulation Explorer (GOCE) satellites (orbit: sun-synchronous, meridional direction, the altitude of ~250 km). Our findings can be summarized as follows.

EPBs frequently occur during both the March and September equinoxes. By analyzing the S_4 index of the amplitude scintillation as observed by the ground GPS receivers at the PTK and BDG stations during March and September from 2011 to 2015, we found an equinoctial asymmetry in the zonal distribution of the scintillation occurrence. That is, the scintillation occurrence in March is more pronounced in the western azimuth than in the eastern azimuth, as observed from both stations, whereas no such zonal scintillation difference is discernible in September. The westward preference of the scintillation occurrence could be due to the westward tilting of the plasma bubbles. Therefore, our observational results suggest that the plasma bubbles are tilted westward in altitude/latitude with more in March rather than in September. Further investigations regarding the latitudinal variations in the zonal scintillation drifts estimated using three closely spaced GPS receivers at the KTB station and the neutral thermospheric wind derived from the CHAMP satellite for the Indonesian sector show that the latitudinal profiles of both the scintillation drift and the neutral wind velocities decreased with increasing magnetic latitudes. Interestingly, the latitudinal gradients of both the scintillation drift and neutral wind were steeper in March than in September. These observations strengthen the idea that the plasma bubbles are tilted westward more in March than in September. Therefore, we suggest that this further westward plasma bubble tilting in March could be responsible for the observed westward preference of the scintillation occurrence. We suggest that the equinoctial asymmetry in the thermospheric winds plays an important role in the equinoctial asymmetry in the occurrence of ionospheric irregularities.

The second study investigates the relationship between the pre-reversal enhancement (PRE) magnitude and latitudinal extension of the EPBs by employing two ionosondes deployed at CPN and BCL and GPS receivers installed at the KTB, PTK, and BDG stations. The PRE is an enhancement of the evening eastward electric field in the equatorial ionosphere. From the ionosonde, the magnitude of the PRE is represented by the peak of *h'F* at 3 MHz (the altitude of the bottomside *F*-region) and the upward velocity of the equatorial *F*-region around sunset, whereas the duration of the PRE is defined as the time duration of increasing *h'F* around sunset until a peak is reached prior to the point at which *h'F* descends. GPS receivers, which observe ionospheric scintillation, are employed to estimate the latitudinal extension of the EPBs, assuming that the EPBs are the major source of scintillations. Empirically, our findings show that the plasma bubble reaches 10°–25° magnetic latitudes under the following conditions: (1) the maximum value of *h'F*(3 MHz) varies from 250 to 450 km and (2) the maximum PRE strength ranges from 10 to 70 m/s. The maximum latitudinal extension of the plasma bubble is satisfactorily correlated with the magnitude of the PRE but not with the duration of the PRE. We conclude that the key factors of the plasma bubble extension could be the altitude of the bottomside *F*-region and the magnitude of the PRE, not the duration.

In many cases, multiple EPBs appear. The third study aims to disclose the important factors related to the generation of multiple EPB occurrences. We have considered two factors for multiple EPB generation, namely, the PRE strength and the gravity wave (GW) activity embedded in the equatorial bottomside *F*-region. The GW is considered to be a passing acoustic wave that can cause oscillations in the neutral density and wind in the thermosphere and in the plasma density in the *F*-region ionosphere. We have utilized two ionosondes at CPN and BCL and the EAR at KTB to disclose statistically the correlation between the PRE strength and multiple EPB occurrences in Southeast Asia during March and September from 2011 to 2013. We found that although the increasing PRE strength results in an increase in the probability of multiple EPB occurrences, the multiple EPB occurrences may need initial seeding. By analyzing the zonal spacing of the two consecutive EPBs, we found that the zonal spacing between two consecutive EPBs ranges from 100 km to 800 km with the maximum occurrence of approximately 200–400 km. This finding regarding the distribution in the zonal spacing of the EPBs is consistent with the dominant wavelengths of the zonal structure of plasma density perturbation referred to as a large-scale wave structure (LSWS) from previous studies [e.g., Tulasi Ram et al., 2014]. We then suggest that the presence of the LSWS, which provides the initial seeds, may help generate multiple EPB occurrences. Next, we classified the zonal spacing of the EPBs into two groups, namely, nights with weaker and stronger PREs. We found that the distribution of the zonal spacing of the EPBs is concentrated at 200–400 km for both nights with weaker and stronger PREs. Interestingly, the distribution of the zonal spacing of the EPBs longer than 200–400 km is contributed by the nights when stronger PREs occur. This finding implies that the zonal spacing of the EPBs for nights with weaker PREs well resembles the wavelength of the LSWS. For the stronger PRE, the EPBs not only occur at the crest of the LSWS but also tend to be longer. Furthermore, we have compared the average power spectrum

of GW activity for nights with and without multiple EPB occurrences by analyzing the zonal wind data from the GOCE satellite. The average power spectra of the GW component from the wind data measured by the GOCE satellite between nights with and without multiple EPB occurrences are comparable. We conclude that the multiple EPB occurrences are not related to the stronger GW activity, at least the GW component in the meridional direction at the dusk sector in the equatorial bottomside *F*-region.
Finally, from the results from our studies, we generally conclude that the seasonal and latitudinal/altitudinal variations in the thermospheric neutral wind and the evening zonal eastward electric field (PRE) could control the morphological features of the plasma bubble and the PRE and the presence of the LSWS could be the important factors for multiple EPB generation. The observation of oscillation in the thermospheric neutral wind associated with gravity wave activity showed that the generation of multiple EPBs does not depend on the amplitude of the neutral wind oscillation caused by gravity waves.