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Medium-Scale Traveling Ionospheric Disturbances and Plasma Bubbles Observed by an All-Sky Airglow Imager at Yonaguni, Japan

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ABSTRACT

We report on nighttime airglow imaging observations of the low latitude ionosphere by means of a 630-m all-sky imager installed in March 2006 at Yonaguni, Japan (24.5 N, 123.0 E; 14.6 N geomagnetic), about 100 km east of Taiwan. The imager detected medium-scale traveling ionospheric disturbances (MSTIDs) for about 7 hours on the night of 26 May 2006. A dense GPS network in Japan also observed the same MSTID event on this night. The imager and GEONET data indicate that most of the MSTIDs propagated southwestward from the north of Japan to the south of Yonaguni and Taiwan over 4000 km, with a southern limit of 19 N (geomagnetic latitude 9 N) or lower. On the night of 10 November 2006, the imager observed two weak emission bands that were embedded on the F-region anomaly crest to the south of Yonaguni. The simultaneous electron density profiles from the FORMOSAT-3/COSMIC mission demonstrate that the weak emission bands are due to density depletions in equatorial plasma bubbles. These case studies suggest that the Yonaguni imager in collaboration with other instruments is very suitable for the study of ionospheric disturbances in and around the northern F-region anomaly crest.

Key words: Traveling ionospheric disturbance, Plasma bubble, Airglow, Total electron content

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1. INTRODUCTION

Traveling ionospheric disturbances (TIDs) with horizontal scales of > 100 km in the F-region ionosphere have been extensively studied by means of radio techniques (Hunsucker 1982; Hocke and Schlegel 1996). These techniques have clarified various characteristics of TIDs although most of the observations have been made at a fixed location with a single method. Recent new observation techniques using all-sky CCD imagers and Global Positioning System (GPS) satellites have brought about a new era of TID studies. Now Japan has a network of 630.0-nm all-sky airglow imagers capable of imaging nighttime F-region plasma distribution, and an extremely dense GPS network (GEONET: GPS Earth Observation Network) of about 1200 receivers, which provides the data on total electron content (TEC) between GPS altitude (20200 km) and the ground. These networks, covering the mid-latitude region over Japan, have largely contributed toward disclosing new features of two-dimensional nighttime medium-scale TIDs (MSTIDs) with wavelengths of 150 - 600 km over a very wide area (e.g., Kubota et al. 2000; Saito et al. 2001; Ogawa et al. 2002; Shiokawa et al. 2002). Generation mechanism of MSTIDs remains unclear and is still controversial. Though TIDs have been long believed to be the ionospheric manifestations of atmospheric gravity waves (Hines 1960), recent observations have suggested that polarization electric fields in the F-region play an important role in the development of nighttime MSTIDs (Shiokawa et al. 2003; Otsuka et al. 2004). We need more observations and theoretical works to understand the MSTID generation mechanism.

Plasma bubbles are depletions in plasma in the nighttime

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equatorial F-region. It is known that ionospheric scintillations due to bubbles give severe effects on earth-space radio communications, satellite positioning, etc. Well-developed giant plasma bubbles have been simultaneously detected at mid-latitudes in Japan and Australia (Otsuka et al. 2002; Shiokawa et al. 2004; Ogawa et al. 2005). However our knowledge of bubble behavior at low latitudes in East Asia is still poor, mainly for lack of suitable observation equipment. Continuous bubble monitoring by means of optical equipment together with radio techniques is necessary to clarify bubble characteristics.

To monitor ionospheric disturbances routinely at low latitude in East Asia, we installed an all-sky airglow imager on Yonaguni Island, Japan (24.5 N, 123.0 E; 14.6 N geomagnetic), about 100 km east of Taiwan, in March 2006. This paper gives the first results from this imager to demonstrate capability for monitoring MSTIDs and plasma bubbles in a wide area over Yonaguni and Taiwan, and shows an example of a bubble simultaneously observed by the imager and the FORMOSAT-3/COSMIC mission.

2. OBSERVATIONS

The Yonaguni all-sky airglow imager, which belongs to the Electronic Navigation Research Institute of Japan, has been operated as part of the Optical Mesosphere Thermosphere Imagers (OMTIs) system of the Solar-Terrestrial Environment Laboratory, Nagoya University (e.g., Shiokawa et al. 2000). The imager consists of seven filters (OI 557.7 nm, OI 630.0 nm, OI 777.4 nm, OH bands 720 - 910 nm, Na 589.3 nm, H 486.1 nm, and background 572.5 nm) on a wheel, a fish-eye lens with a field of view of 180 , and a thinned and back-illuminated cooled-CCD camera with 512 512 pixels. The OI 630-nm all-sky airglow images, with which we are concerned, were taken every 5.5 min with an exposure time of 165 s. Figure 1 shows a field of view (FOV) of the imager with a diameter of about 1100 km at 250 km altitude for a zenith angle of 65 .

2.1 Medium-Scale Traveling Ionospheric Disturbances

The Yonaguni imager observed MSTIDs for about 7 hours from 1200 to 1900 UT (= LT - 8 hours) on the night of 26 May 2006. In Fig. 2, twelve 630-nm all-sky images obtained during 1308 - 1627 UT are mapped onto a horizontal plane in geographic coordinates by assuming an emission altitude of 250 km, below the F-layer peak, around which the volume emission rate of the OI 630-nm airglow is known to have a

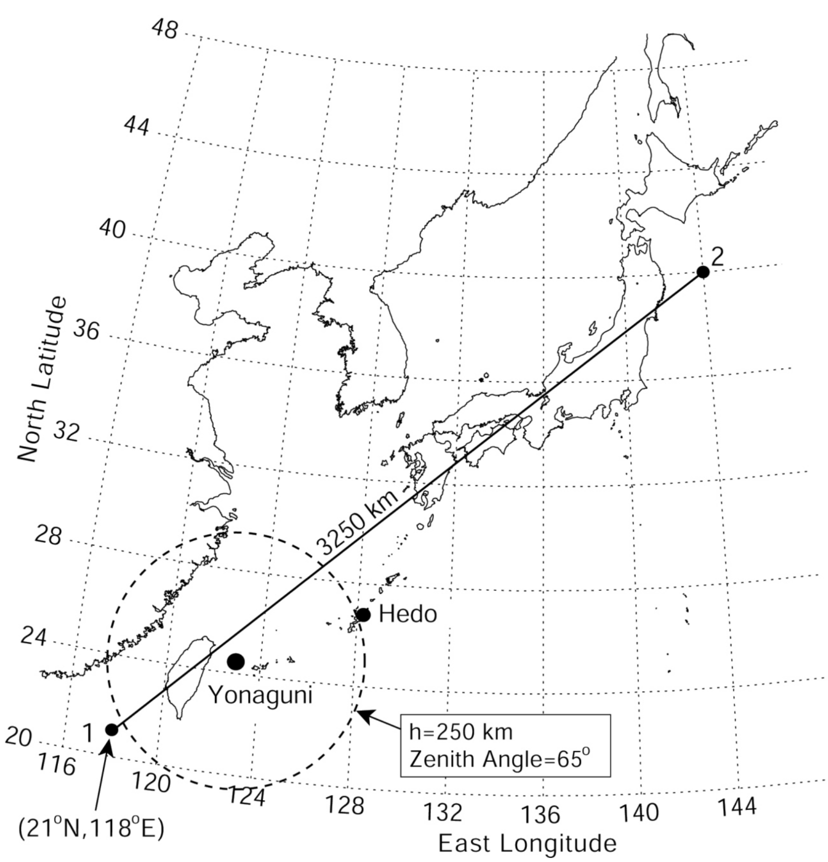

Fig. 1. Field of view (FOV; dashed circle) of an all-sky imager located on Yonaguni Island, Japan. The FOV has a diameter of about 1100 at 250 km altitude for a zenith angle of 65 . An all-sky imager was temporarily installed at Hedo in Okinawa in August 1999 (Shiokawa et al. 2002).

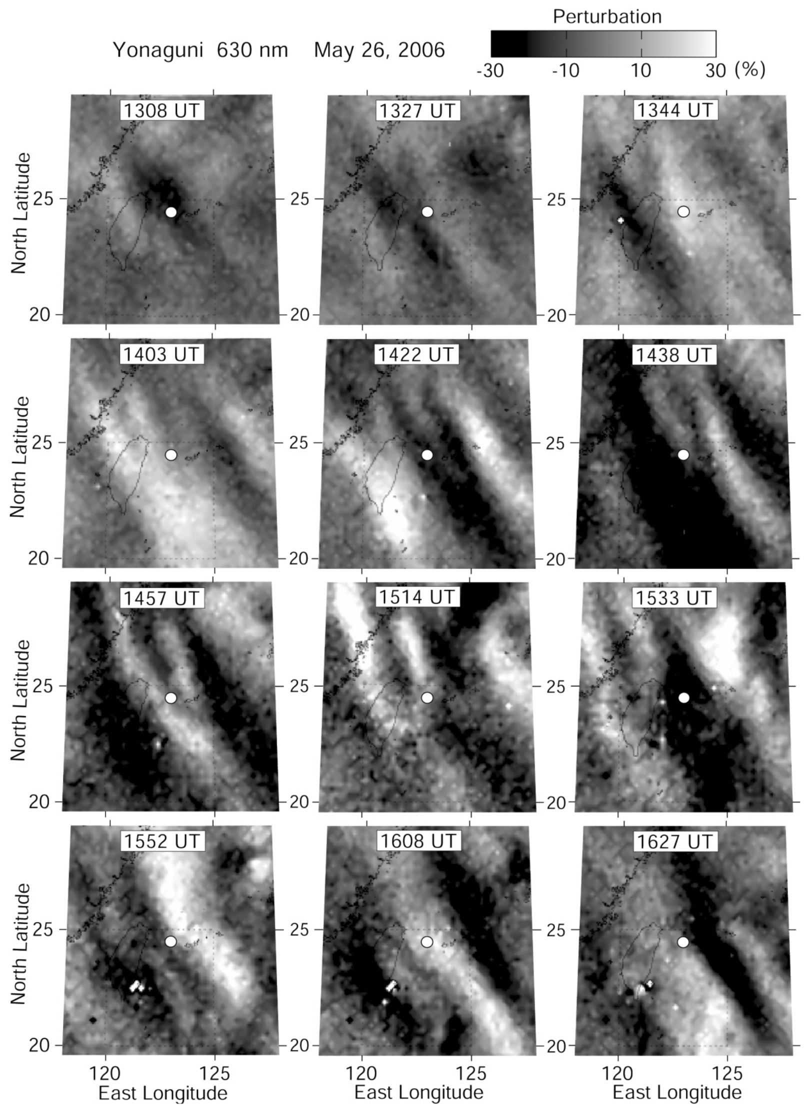

Fig. 2. Time variation of 630-nm airglow intensity perturbation map over Yonaguni (marked by a white circle) on the night of 26 May 2006. All-sky images are mapped on geographic coordinates by assuming an emission altitude of 250 km. Perturbation amplitude with plus (minus) sign corresponds to enhanced (suppressed) electron density.

maximum (e.g., Ogawa et al. 2002). To highlight wavy structures in each image, perturbation component, that is, $(I - I_B) / I_B$ (in %) where I is the measured intensity and I_B is the one-hour running average of I, is displayed. Since the 630-nm emission rate at around 250 km altitude is proportional to the electron density, various structures in Fig. 2 represent the electron density fluctuations in the F-region. It is clearly observed that MSTIDs with amplitudes between -30 and +30%, a wavelength of about 500 km, and phase fronts aligned along NW-SE propagated from NE toward SW with time while changing the perturbation amplitude and wave structure.

GEONET operated by the Geographical Survey Institute of Japan is a dense network of about 1200 GPS receivers distributed in Japan. It provides total electron content (TEC) data every 30 s in a wide area of the ionosphere over Japan on a routine basis. Saito et al. (1998, 2001) clearly demonstrated that GEONET TEC data are very useful for the study of MSTIDs over Japan. Figure 3 displays time variation of the GPS-TEC map on the night of 26 May 2006 when the Yonaguni imager detected MSTIDs. Each map shows a spatial distribution of the perturbation component that is defined as $(TEC - TEC_B) / TEC_B$ (in %) where TEC is the measured TEC and TEC_B is the one-hour running average of TEC. Two or three GPS satellites were available to construct the maps in Fig. 3. In the figure, MSTIDs with wavelengths of a few hundred to about 500 km, phase fronts aligned along NW-SE and perturbation amplitudes between -10 and +5% propagate southwestward toward Yonaguni. The GPS-TEC map at 1420 UT in Fig. 3 is overlaid with the Yonaguni

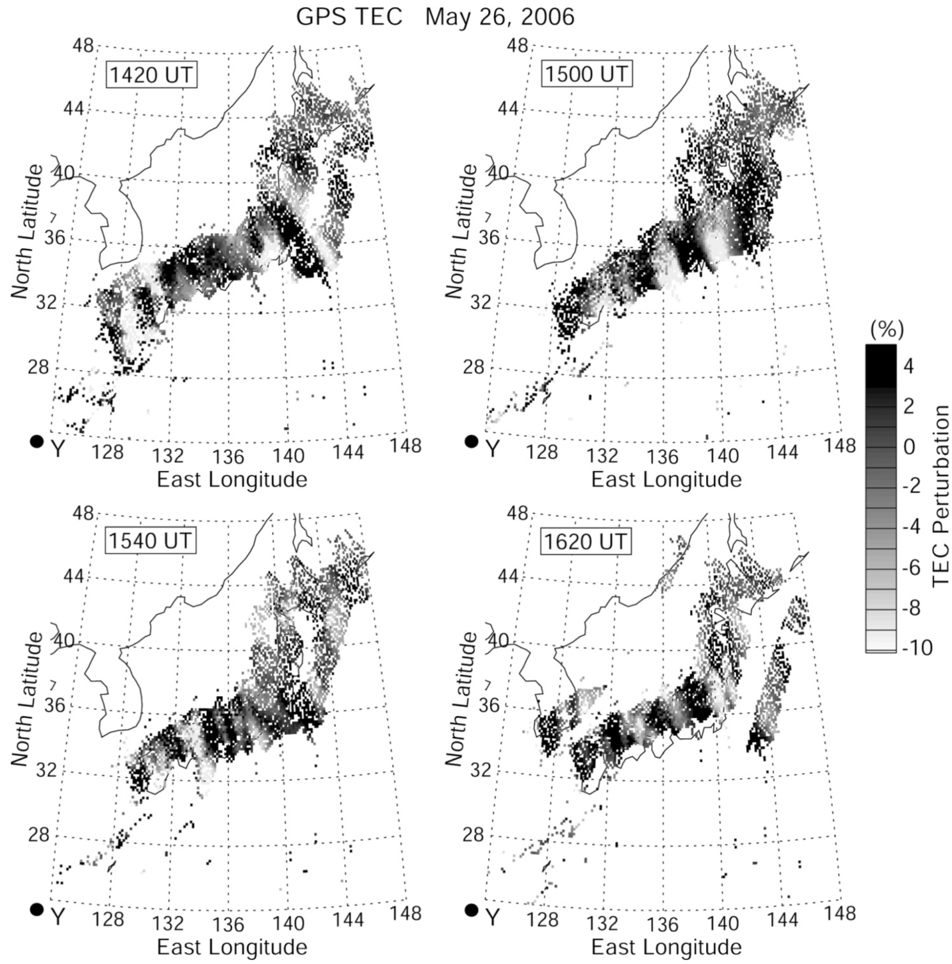

Fig. 3. Time variation of GPS-TEC perturbation map over Japan on the night of 26 May 2006. Perturbation amplitude (in %) with plus (minus) sign corresponds to enhanced (suppressed) TEC. The location of Yonaguni is indicated by a solid circle in each map.

all-sky image at 1422 UT (Fig. 2) in Fig. 4, where as many as 10 wave fronts of MSTIDs can be seen between 20 and 46 N. Figure 4 together with Figs. 2 and 3 indicates that MSTIDs were generated somewhere at latitudes higher than 46 N (the northernmost latitude of Japan) and propagated southwestward through Japan and Taiwan.

To see detailed MSTID characteristics, Fig. 5 plots time variations of the airglow intensity and TEC perturbations for 8 hours along the line with a length of about 3250 km from point 1 (21 N, 118 E) to point 2 (40 N, 144 E) shown in Fig. 1. The MSTIDs at earlier times over Yonaguni seem to have originated near Yonaguni, and those at later times over the mainland of Japan dissipated during propagation before arriving at Yonaguni. Though the wave structures are not always continuous in time and distance because of the sparse TEC data between 1400 and 1600 km, we believe that most of MSTIDs propagated from the north of Japan toward the south beyond Yonaguni and Taiwan over 4000 km, with a southern limit of 19 N (geomagnetic latitude 9 N) or lower. They have wavelengths of 300 - 600 km (mostly, about 500 km), periods of 40 - 60 min, and average apparent velocity of about 120 m s^{-1} as indicated by the white dashed line in Fig. 5. The average phase velocity perpendicular to the phase fronts is about 100 m s^{-1} by considering the phase fronts that are not perpendicular to the line depicted in Fig. 1.

2.2 Plasma Bubbles

The Yonaguni all-sky imager observed equatorial plasma bubbles on the night of 10 November 2006. The upper part of Fig. 6 shows time variation of the 630-nm airglow intensity map. The airglow intensity is expressed by the raw output counts of the CCD detector. The bright area in each map corresponds to the northern F-region anomaly crest. As can be seen, the anomaly gradually subsided with time. The airglow intensity of bubbles is usually lower than that of the background ionosphere because the electron density in a bubble is quite low. At 1122 and 1157 UT there existed two plasma bubbles (the gray N-S extended areas with raw counts,

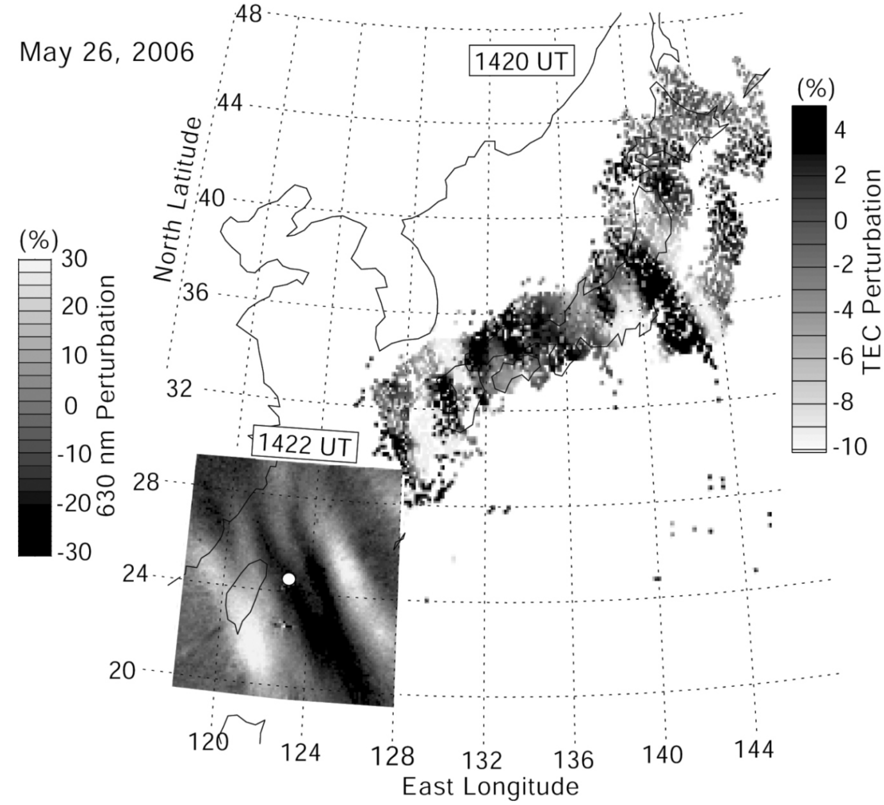

Fig. 4. GPS-TEC perturbation map over Japan at 1420 UT 26 May 2006 and 630-nm airglow intensity perturbation map over Yonaguni at 1422 UT on the same day.

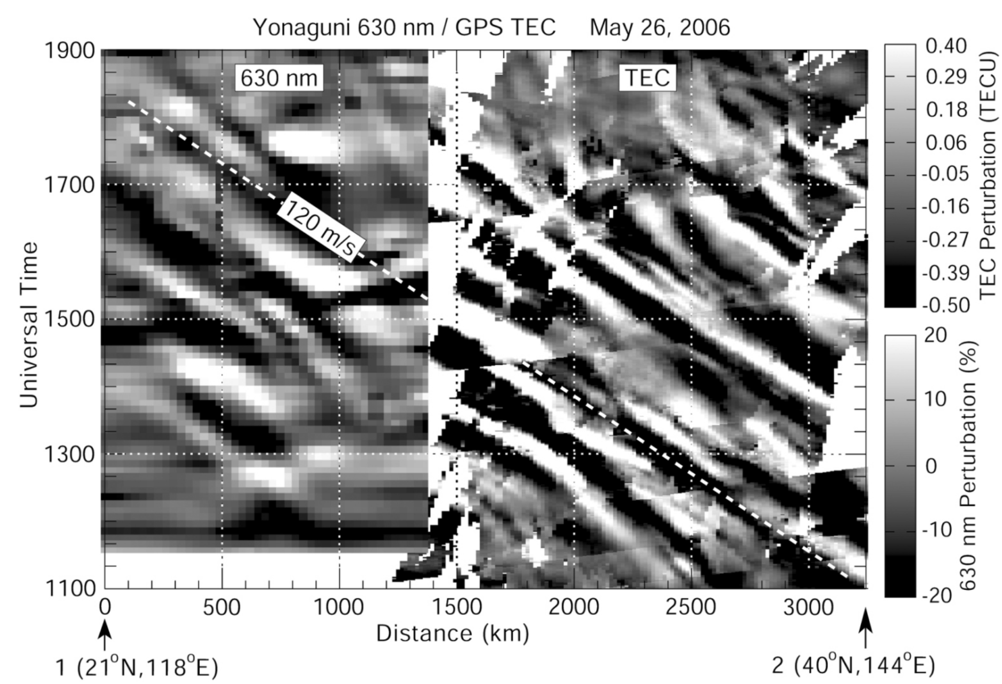

Fig. 5. Time variations of 630-nm intensity and TEC perturbations along a line from point 1 (21 N, 118 E) to point 2 (40 N, 144 E) in Fig. 1. TEC perturbation amplitude is expressed in units of TECU (1 TECU = 10^{16} electrons m^{-3}).

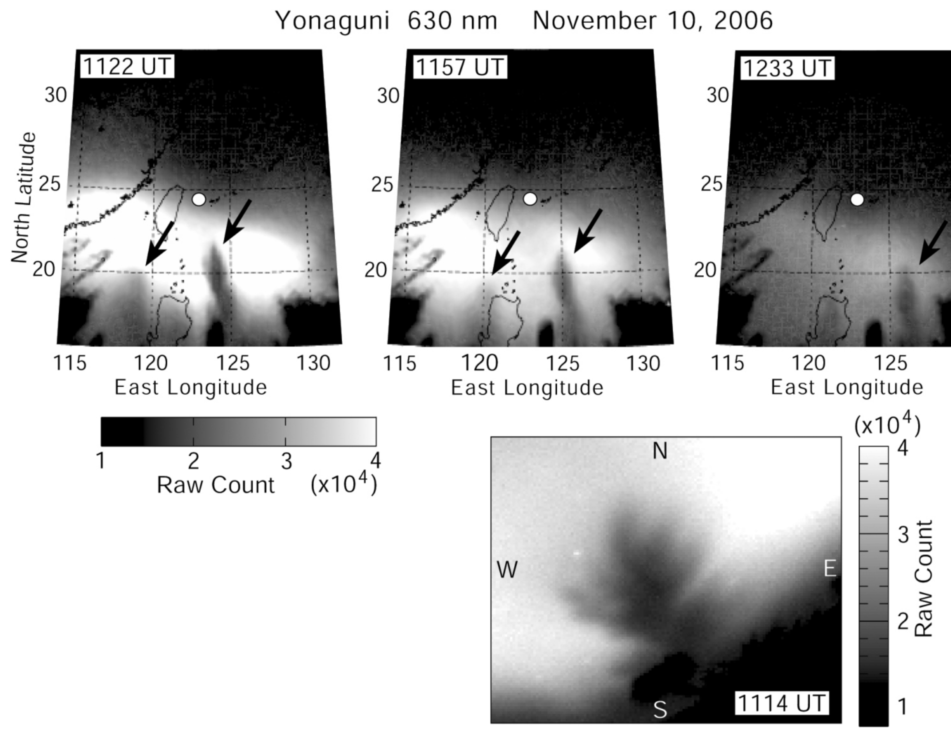

Fig. 6. Time variation of 630-nm airglow intensity map over Yonaguni on 10 November 2006. As indicated by arrows, there exist two plasma bubbles at 1122 and 1157 UT and one at 1233 UT. Bright area corresponds to the northern F-region anomaly crest. Some dark regions without temporal variation below 20°N are due to trees near the observation site. All-sky image at 1114 UT is enlarged at the bottom to give a close up view of the bubble. Airglow intensity is expressed by raw output counts of the CCD detector.

as indicated by the arrows), separated by about 500 km, with an east-west width of about 100 km; they were faint at 1044 UT (not shown). These bubbles moved eastward at about 50 m s^{-1}. The western bubble disappeared before 1233 UT, and the eastern one did after 1308 UT. The all-sky image at 1114 UT is enlarged in the lower part in Fig. 6, where the bubble exhibits complicated cactus-like structures, a characteristic of plasma bubbles.

During this bubble event, some electron density profiles derived from GPS radio occultations using the FORMOSAT-3/COSMIC mission (Schreiner et al. 2007) are available. Figures 7a and b display 630-nm airglow intensity maps at 1138 and 1157 UT, respectively. The bright areas correspond to the northern F-region anomaly crest. Figure 7c shows four altitude profiles of the electron density at times close to these times. Each electron density profile was determined from the radio occultations on the ray tangent path (solid curve) in Figs. 7a and b. The process to obtain the density profile from COSMIC was described by Schreiner et al. (1999). Figure 7 indicates the following: (1) the 1132 UT electron density profile with a maximum of 1.15×10^6 cm^{-3} at 350 km altitude represents the profile in and around the crest without bubbles. (2) The densities in the 1140a and 1204 UT profiles with a maximum of about 8×10^5 cm^{-3} at 350 km are lower than the 1132 UT case. These profiles may exhibit the profile in the south of the crest though the ray tangent paths cross partly the faint bubble at around 120°E. (3) The densities (a minimum of about 5×10^5 cm^{-3}) between 300 and 450 km altitude in the 1140b UT profile are lowest among the four profiles, because the ray tangent path crosses the bubble at around 125°E. Figure 7c indicates density to decrease with decreasing altitude below the F-layer peak. Note that the 630-nm emission altitude is assumed to be around 250 km (see above).

3. DISCUSSION AND CONCLUDING REMARKS

The observational results are summarized as follows:

(1) MSTIDs were observed for about 7 hours on the night of 26 May 2006 by the imager at Yonaguni. GEONET also detected MSTIDs on the same night. By combining imager data with GEONET data, it is found that these MSTIDs had a wavelength of about 500 km, periods of 40 - 60 min, and an average phase velocity of about 100 m s^{-1}. Most of the MSTIDs propagated southwestward from the north of Japan to the south of Yonaguni and Taiwan over 4000 km, with a southern limit of 19°N (geomagnetic latitude 9°N) or lower.

(2) On the night of 10 November 2006, the imager detected two equatorial plasma bubbles, separated by about 500 km, that were embedded in the F-region anomaly crest to the

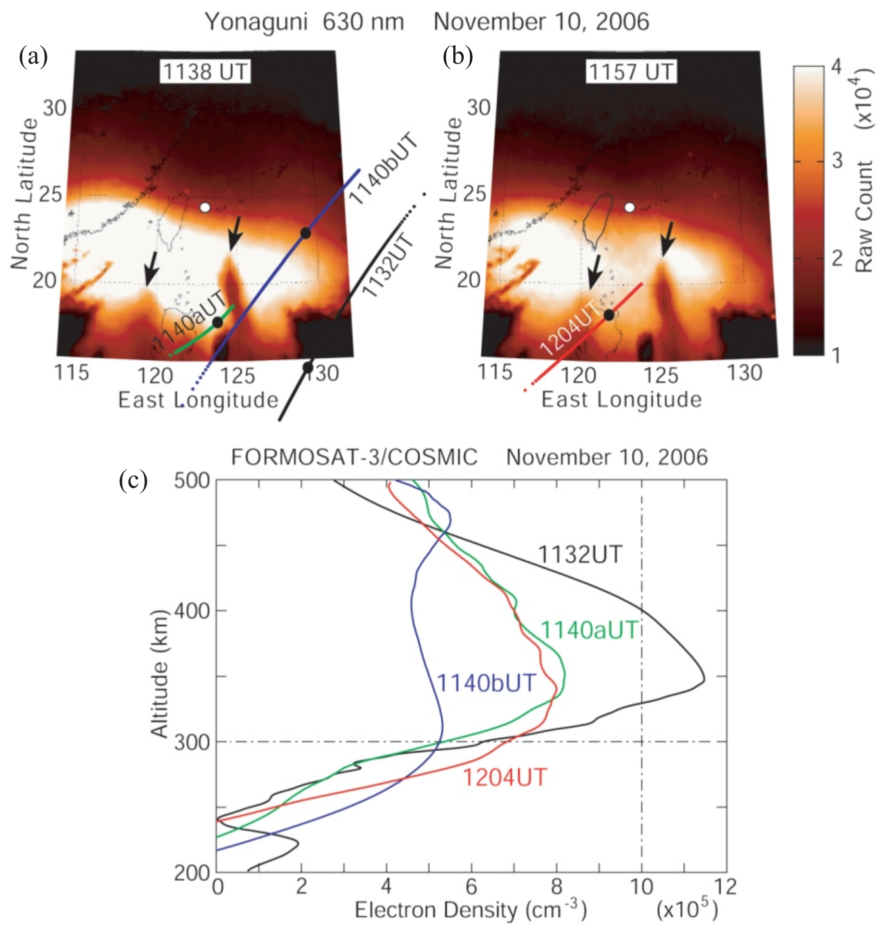

Fig. 7. 630-nm airglow intensity map over Yonaguni at: (a) 1138 UT and (b) 1157 UT on 10 November 2006. Plasma bubble is indicated by arrow. (c) Four altitude profiles of the electron density at times close to these times. Each profile was determined on the ray tangent path (solid curve) shown in (a) and (b).

south of Yonaguni. The bubbles with an east-west width of about 100 km moved eastward at about 50 m s^{-1}. Electron density profiles obtained by the FORMOSAT-3/COSMIC mission well correspond to two-dimensional distribution of the airglow intensity, and show that the density is surely suppressed within the bubble detected by the imager.

In recent years, MSTIDs over Japan have been well studied by means of, in particular, all-sky imagers (e.g., Kubota et al. 2000; Shiokawa et al. 2003), GEONET (e.g., Kotake et al. 2006), and both of imager and GEONET (e.g., Saito et al. 2001; Ogawa et al. 2002; Shiokawa et al. 2002). Based on simultaneous observations of MSTIDs with GEONET and an all-sky imager temporarily installed at Hedo in Okinawa (26.9 N, 128.3 E; 17.0 N geomagnetic; see Fig. 1) in August 1999, Shiokawa et al. (2002) suggested that the southern limit of the southwestward propagation of MSTIDs from mainland Japan was possibly around 18.0 N geomagnetic latitude. Our result (item 1), however, indicates the southern limit to be lower than 9 N geomagnetic latitude, and shows for the first time that MSTIDs detected over Japan can propagate southwestward beyond Taiwan over 4000 km. It seems that the propagation distance and southern limit of propagation depend on MSTID wave amplitudes as well as background ionospheric conditions such as electron density distribution and thermospheric wind. We do not know from the current observations where and how the MSTIDs were generated. Auroral activity at high latitudes seems not to be responsible for the generation because 3-hour K_p indices were quiet and 0+, 1, 1, and 1- during 0900 - 2100 UT 26 May 2006.

We have assumed that the OI 630-nm airglow emission has a maximum intensity at around 250 km. From model calculations, Ogawa et al. (2002) confirmed this assumption. At around 1501 UT when the MSTIDs were observed at Yonaguni (Fig. 2), the electron density profile at around 26.5 N, 104.0 E, about 1800 km NNW from Yonaguni, which was obtained by the FORMOSAT-3/COSMIC mission, indicates a peak altitude of 370 km with an electron density of 4.1 10^5 cm^{-3}. The three electron density profiles displayed in Fig. 7c show the peak altitude of around 350 km.

These observations suggest that the OI 630-nm emission altitudes are below the F-layer peak.

Plasma bubbles are a common phenomenon appearing in the nighttime equatorial F-region ionosphere after sunset. As is well known, bubble activity in East Asia is highest in equinoctial months in solar maximum (e.g., Gentile et al. 2006). From simultaneous observations of giant plasma bubbles with all-sky imagers in Japan and Australia and 135.6-nm airglow with the IMAGE satellite, Ogawa et al. (2005) have found that plasma bubbles in April 2002 (near solar maximum) moved to the east at about 100 m s^{-1}, had a scale of about 100 km with spacings of 200 - 250 km, and were embedded within plasma structures with a scale of about 1000 km. These geomagnetic conjugate bubbles were situated in the northern and southern anomaly crests, in line with the above item 2.

Continuous monitoring of the ionospheric scintillations of 1.6-GHz GPS radio waves has shown that equinoctial bubbles over Kototabang in Indonesia (0.2 S, 100.3 E; 10.4 S geomagnetic) in 2003 and 2004 appeared during February - March and September - October (Ogawa et al. 2006; Otsuka et al. 2006). The bubble activity after 2004 became weaker with declining solar activity. The solar activity in 2006 is close to minimum so that active bubbles over Kototabang were few, in line with that bubble activity over Yonaguni in autumnal equinoctial months in 2006 was very low. The bubbles in Fig. 6 are tiny, and their eastward velocity of 50 m s^{-1} is very slow, compared with observations (about 100 m s^{-1}) made at Kototabang in 2003 and 2004 (Otsuka et al. 2006). We notice that the bubbles in Fig. 6 might be induced by the geomagnetic storm that began at around 1300 UT 9 November. K_p indices of 5-, 6, and 4 during 0600 - 1500 UT 10 November suggest that the storm was near the maximum phase when the bubbles were observed. A storm-time electric field penetrating into the geomagnetic equator might have triggered the bubble generation (e.g., Huang et al. 2002).

In conclusion, we have presented MSTID and plasma bubble events detected by the 630-nm all-sky airglow imager at Yonaguni, the westernmost island of Japan, close to Taiwan, and demonstrated that the imager in collaboration with the FORMOSAT-3/COSMIC mission is useful for the study of these events occurring in and around the northern F-region anomaly crest. In the future, this imager collaborating with other instruments such as satellites, ground-based radio sounding, etc. will contribute to a better understanding of ionospheric disturbances at low latitudes in East Asia.

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