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Horizontal Shapes of Daytime Mid-latitude Sporadic-*E* Imaged by GPS Total Electron Content Observations in Japan

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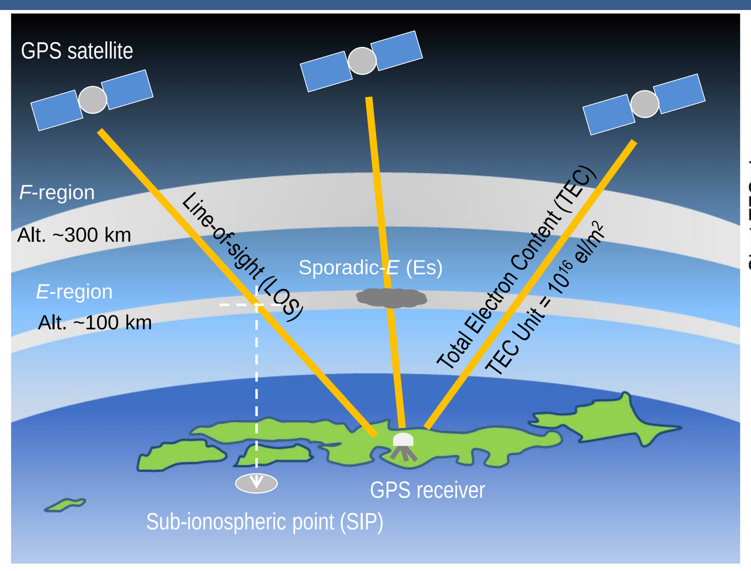
Background & Challenge

GPS/GNSS total electron content (TEC) observation is a strong method for the ionospheric observation. *F*-region (Alt. ~300 km) has been studied extensively. Here we try to detect sporadic-*E* (Es) plasma patches in the *E*-region of the ionosphere (Alt. ~100 km) for the first time ever by using a height constraint technique. It enables the direct imaging of two-dimensional (2-D) horizontal structures of Es which have long been unknown.

Summery

GPS-TEC observations successfully detect and image 2-D horizontal shapes of daytime midlatitude Es over Japan. Es often shows frontal structure with a preferred alignment in the east-west direction. Frontal structures sometimes propagate to north and southward. Close analyses of TEC data revealed small-scale structures and indicate that gradient-drift and Kelvin-Helmholtz instabilities play important roles in the formation of daytime Es patches.

Method : GPS-TEC observation for sporadic-*E* detection



Sporadic-*E* is a densely ionized plasma patch that sporadically appears at an altitude of ~100 km (*E*-region of the ionosphere).

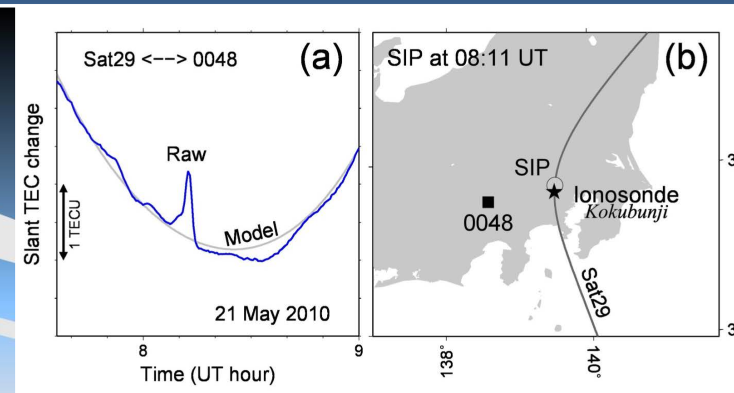


Fig.1 a. Slant TEC time series (observed / model)
b. SIP at 08:11 UT (when TEC pulse was observed)

Advantages of GPS-TEC observation
A dense GPS array in Japan enables two-dimensional imaging of horizontal shapes of sporadic-*E* (Maeda and Heki, *Radio Sci.*, 2014).

Detection threshold	foEs ≈ 17 MHz (Ne ≈ 3.6 x 10^{12} el m^{-3}) Favorable for daytime observation without MSTID.
Resolution	space ~25 km time 30 s

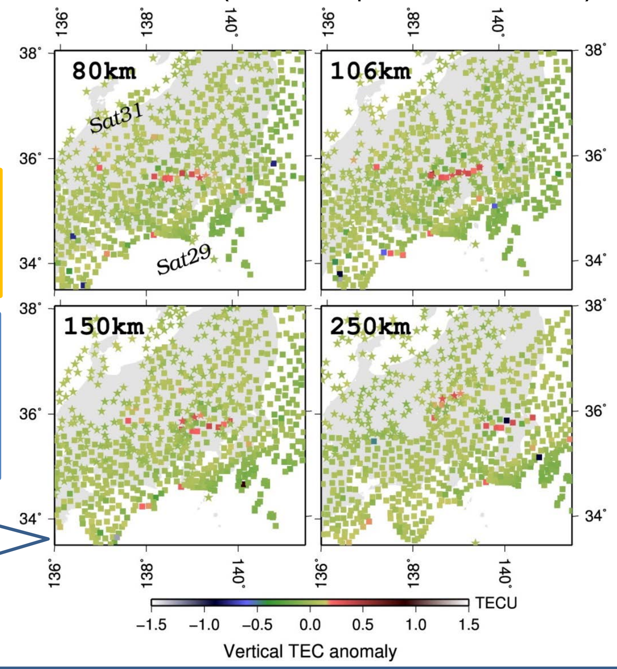
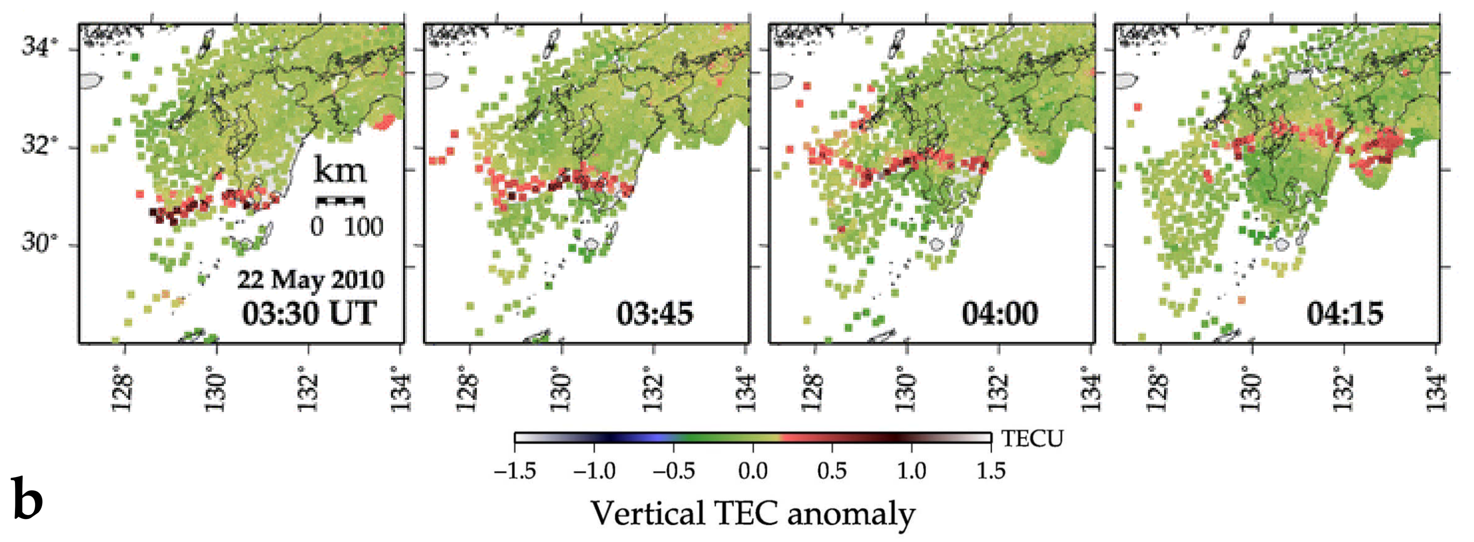


Fig.2 Altitude constraint by using two different satellites. Note that two frontal structures elongated in the east-west direction coincide when SIP altitude is set at 106 km (*E*-region) while gaps emerge at other altitudes.

Large-scale structure: Propagation

a



b

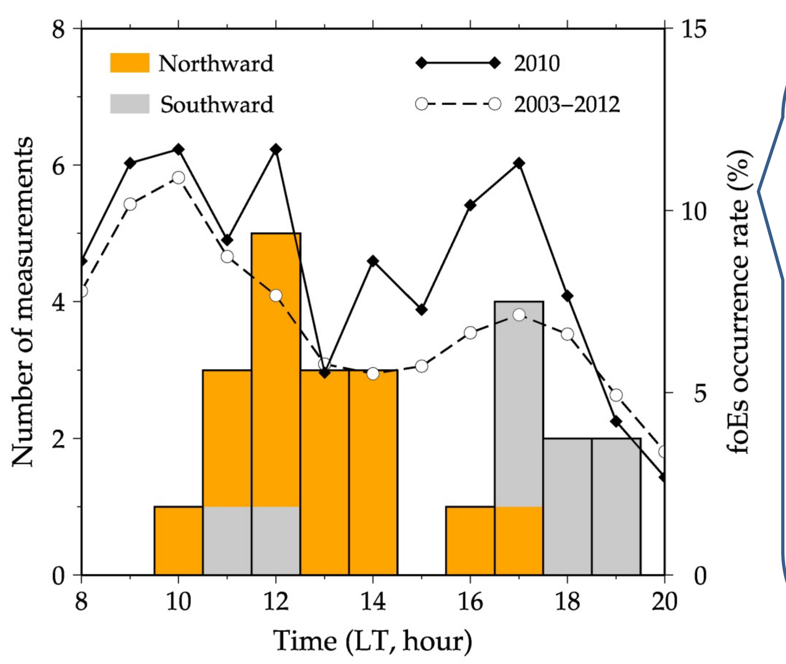


Fig.5
a. Snapshots of vertical TEC anomaly map showing an example of northward propagation of a frontal structure elongated in the E-W direction. In this case, it is clear that the frontal structure propagated to the direction perpendicular to its elongation. Speed and distance of its movement are 40-50 m/s and ~100 km, respectively.
b. Local time dependence of the directions of N-S propagation of Es observed in 2010 (histogram). In the histogram, orange and gray represent the numbers of northward and southward movements, respectively. Curves show occurrence rates of Es derived from foEs data obtained during 2003–2012 (dashed) and 2010 (solid) at the Kokubunji ionosonde (with foEs > 10 MHz). Atmospheric tide is considered to control the direction of Es movement.

Large-scale structure of sporadic-*E* over Japan

Horizontal structure

Characteristics
- Frontal shape
- E-W alignment
- Length ~160 km
- Width ~20 km

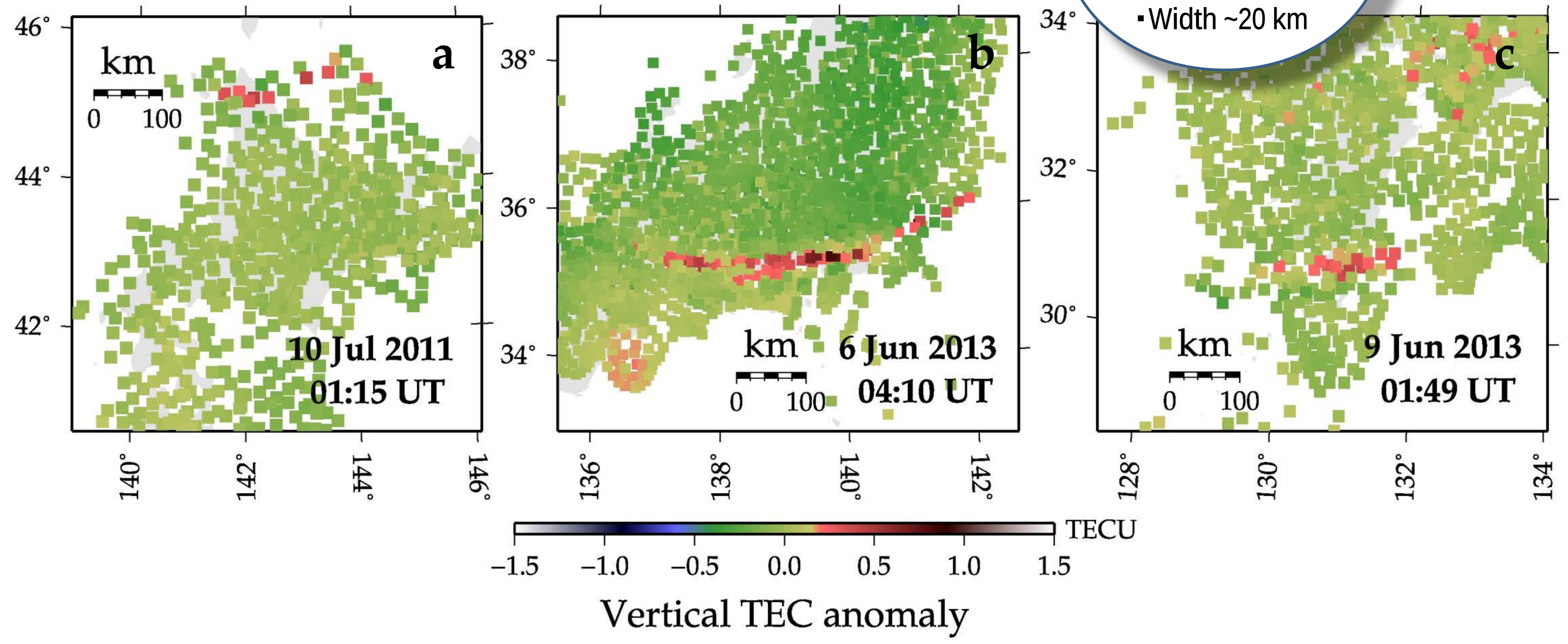
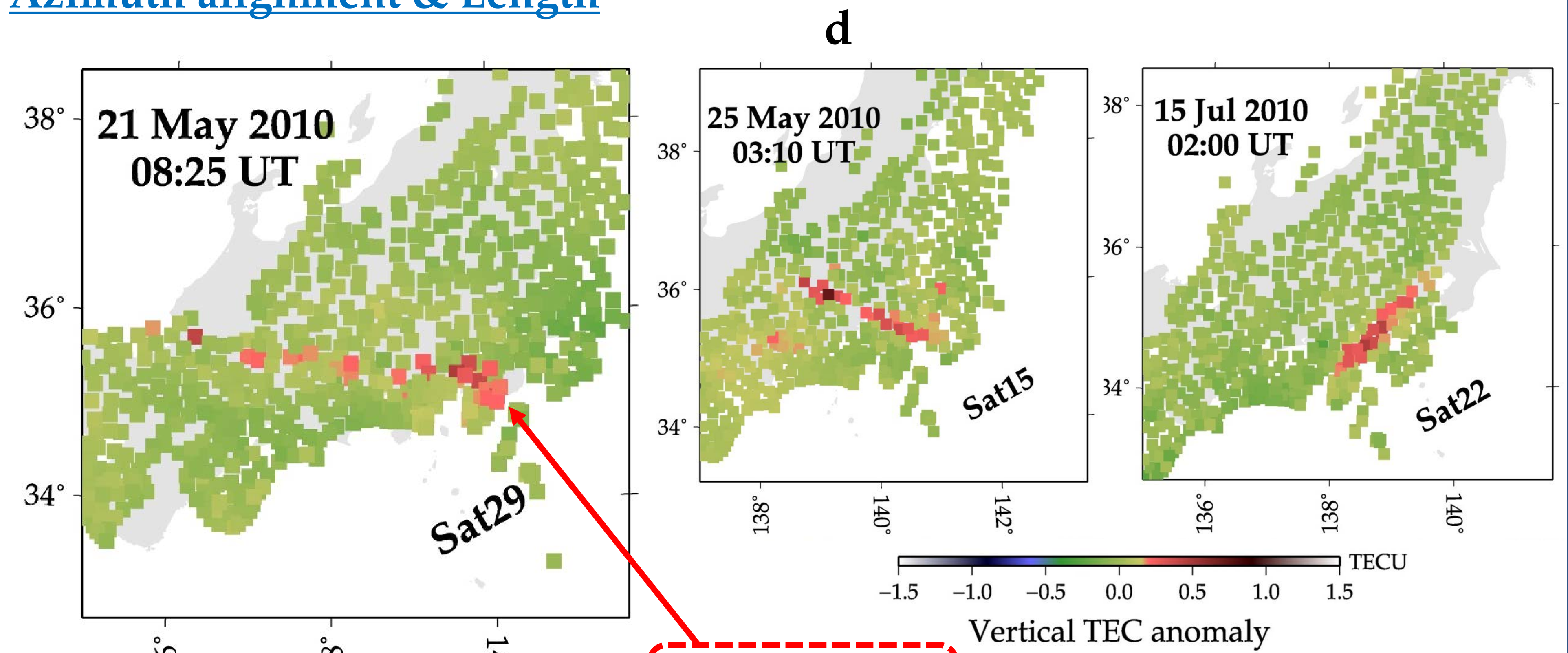


Fig.3 Vertical TEC anomaly maps showing horizontal structures of Es patches that appeared in three different latitude regions, a Wakkanai ~45° N, b Kokubunji ~35° N, and c Yamagawa ~30° N, Japan. Frontal structures are commonly seen with lengths ranging from 100 to 500 km.

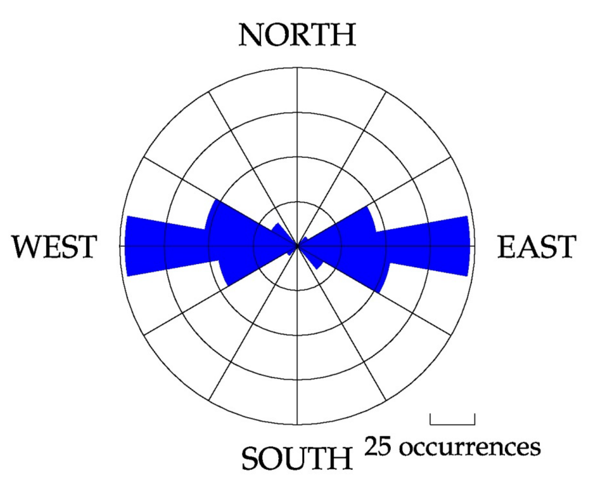
Azimuth alignment & Length

d



Note that the frontal structure is composed of several small-scale patches.

e



f

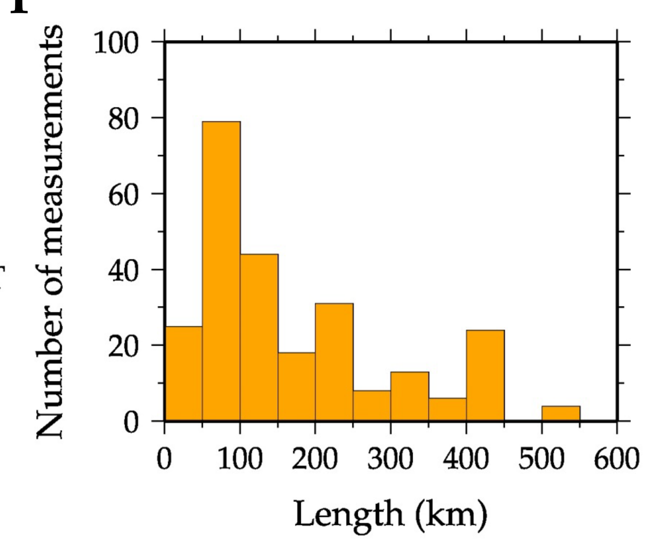


Fig.3
d. Three examples of Es images showing various azimuth alignment of frontal structures observed over the central part of Japan in 2010.
e. Rose diagram showing the number of azimuth alignment of frontal structures observed during 2010. In most cases, structures prefer to elongate in the E-W direction. It should be noted that not a single case is observed which has perfect north-south alignment.
f. Histogram showing the number of measurements for frontal structure lengths. The average and median lengths are ~160 km and ~100 km, respectively.

References

Maeda, J., and K. Heki (2014), Two-dimensional observations of midlatitude sporadic *E* irregularities with a dense GPS array in Japan, *Radio Sci.*, *49*, 28–35, doi:10.1002/2013RS00529.

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Acknowledgments

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Small-scale structure

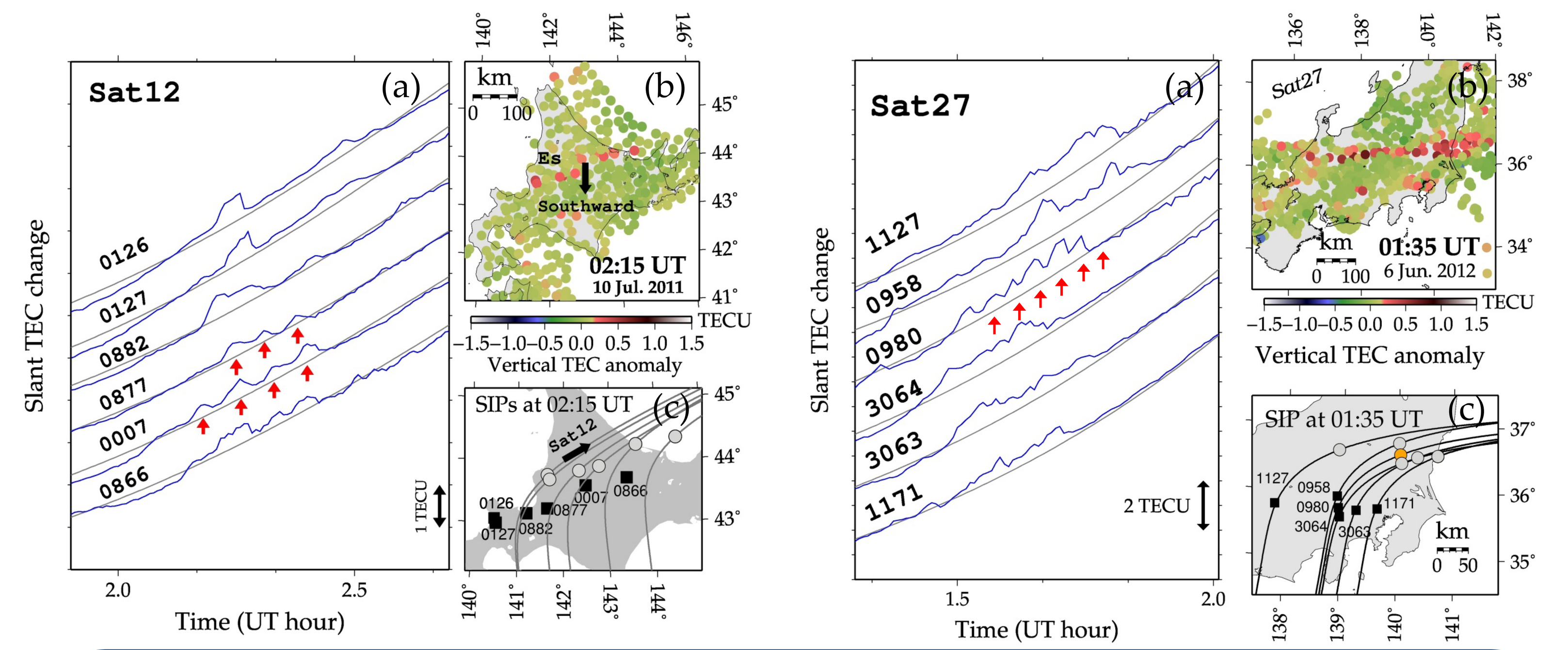


Fig.6
(Left) a. Slant TEC time series drawn by Satellite 12 and six GPS stations, showing typical quasi-periodic (QP) TEC enhancement (especially clear with GPS station 0877 and 0007, pointed by red arrows). b. Vertical TEC anomaly map at 02:15 UT, in which a frontal structure is evident. It elongates in the E-W direction. c. SIP positions with Satellite 12 and six GPS stations at 02:15 UT. SIPs moved east-northeastward, almost tracing the E-W elongation of the frontal structure. These results demonstrates that QP TEC signatures are localized in the central part of the frontal structure. The horizontal separation of QP structure is ~15 km.
(right) a. Another example of along-elongation QP structure observed over the central part of Japan. b. Vertical TEC anomaly map at 01:35 UT, showing an E-W frontal structure which was stationary during the observation. c. SIP positions with Satellite 27 and six GPS stations at 01:35 UT. In a, QP TEC enhancement is clearly observed with the GPS station 0980 while other stations show irregular TEC changes. The location of SIP of 0980 is shown as an orange circle in the SIP map. In this case, either, the QP structure is quite localized in a small region. The horizontal spacing of the QP structure is ~10 km.

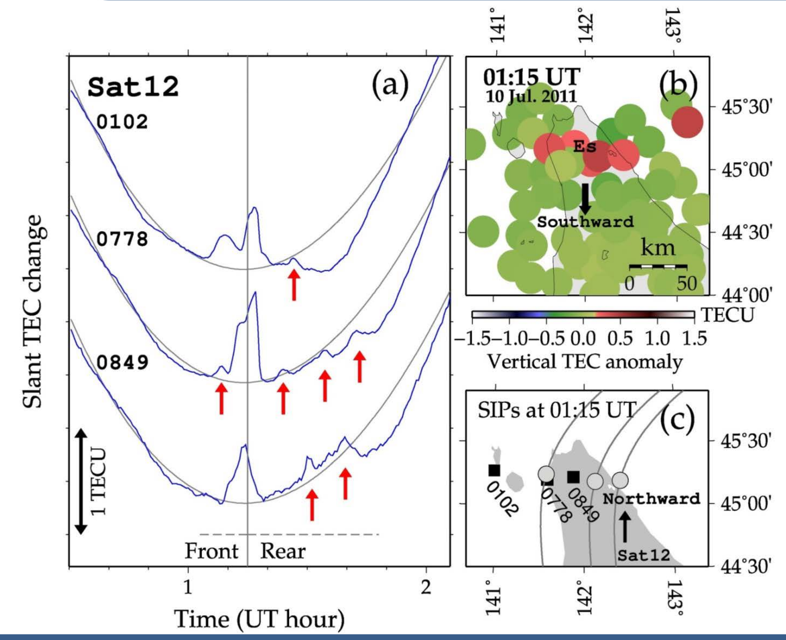
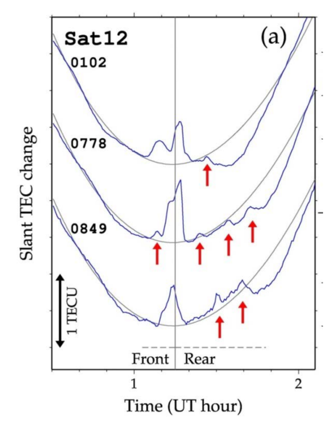


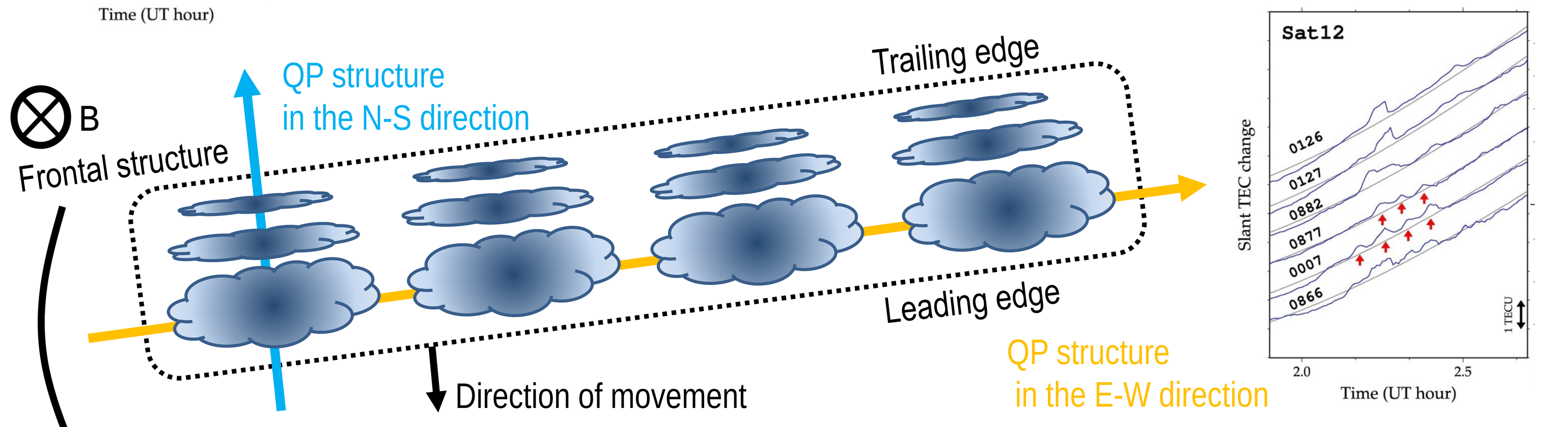
Fig.7
a. Slant TEC time series showing QP TEC enhancement. Dominant peaks are accompanied by several small positive peaks. Since the frontal structure moved southward, the time period in the left/right of the vertical gray line at 01:15 UT represents the front/rear side of the structure (shown with horizontal dashed line).
b. Vertical TEC anomaly map at 01:15 UT, showing a patchy frontal structure elongated in the E-W direction.
c. SIPs of Satellite 12 and three GPS stations at 01:15 UT. Satellite 12 moved northward crossing the frontal structure during the time period shown in a.

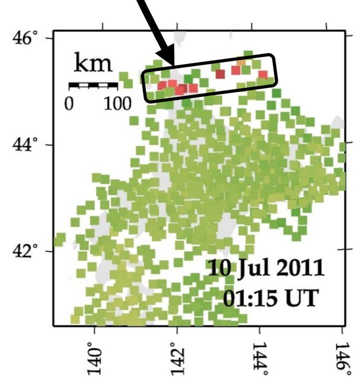
Discussion: Formation of Es patch



Gradient-drift instability

Gradient-drift instability achieves the maximum growth rate when the direction of electron density gradient and the direction of Es patch movement are parallel. In this sense, plasma clouds in propagating Es with steep electron density gradient are supposed to be under the condition of gradient-drift instability. Slant TEC time series (Fig.6a) show that phase front of frontal structure is smooth and the trailing edge is undulated. Small plasma patches (pointed by red arrows in the left figure) are considered to be separated from the undulated trailing edge of the frontal structure.





Kelvin-Helmholtz (KH) instability

It is widely accepted that the formation of Es patches are attributed to zonal wind shear which often create favorable condition for shear instabilities such as the Kelvin-Helmholtz (KH) instability. This implies that wind shears would create wave-like structure that are responsible for QP TEC enhancement observed in this study (Fig.6 & 7). Zonal winds are considered to be the primary driver for the formation of frontal structures elongated in the E-W direction. The KH instability may separate the main plasma cloud into a series of plasma patches under the presence of strong wind shear, e.g., Richardson number lower than 0.25.