SuperDARN Hokkaido radar observations of ionospheric disturbances after the 2011 Tohoku Earthquake

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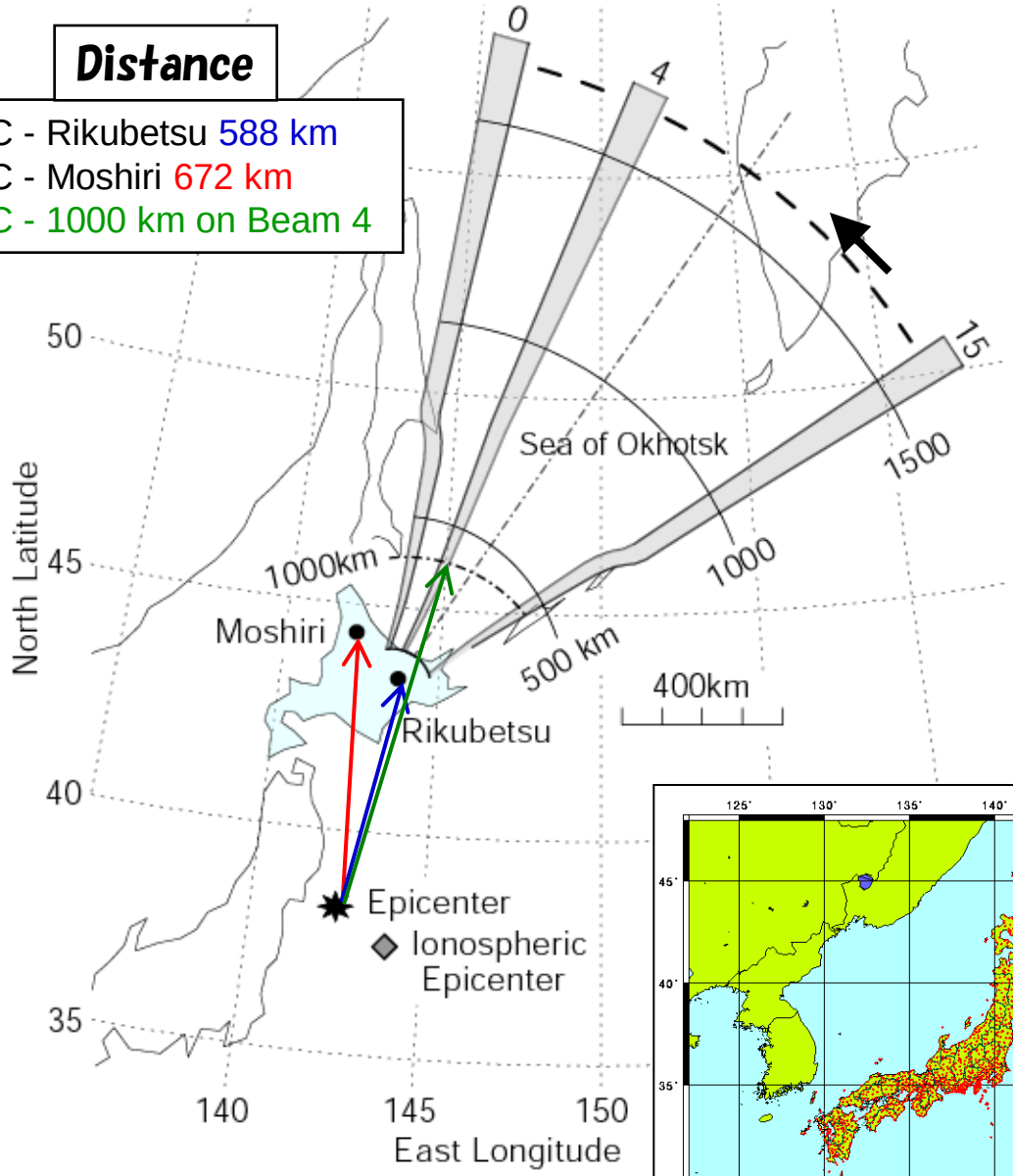
- Historical Earthquake : 0546:23 UT (1446:23 JST) on 11 March 2011, M_W = 9.0, in the off the Pacific coast of Tohoku
- Strong modulation of daytime sea-scatter echoes due to waves from below
- HF radar echo modulation induced by Rayleigh waves（6.7 ~ 1.8 km /s） and atmospheric gravity waves (< 350 m/s)
- Doppler velocity oscillations (2 ~ 4 min) caused by acoustic resonance between the ground surface and the lower thermosphere
- Comparison between radar and GPS-TEC observations

Initial results have been recently reported by Nishitani et al. (2011)

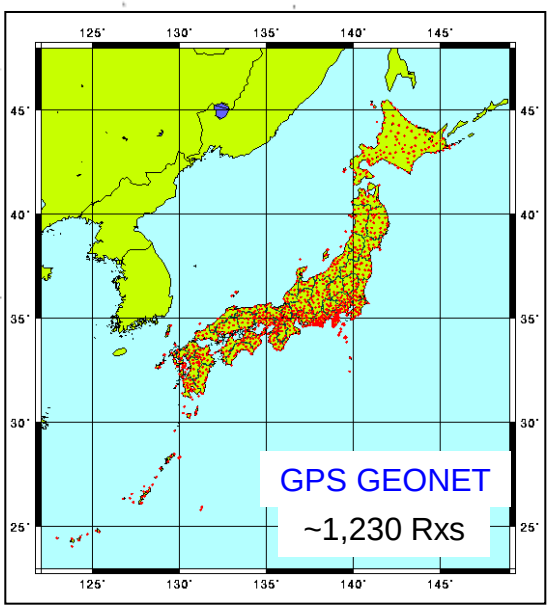
Distance

EC - Rikubetsu 588 km
EC - Moshiri 672 km
EC - 1000 km on Beam 4

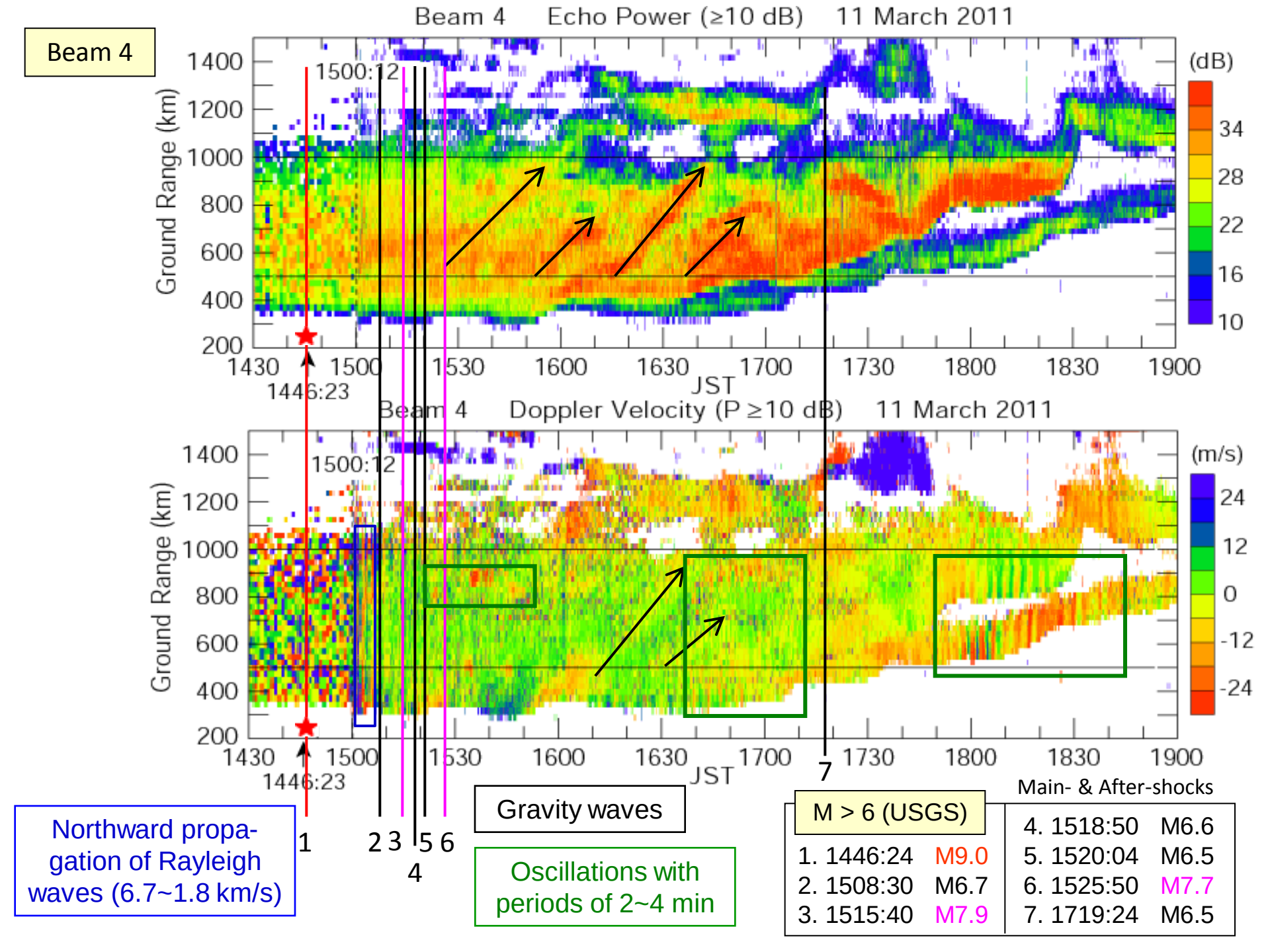


THEMIS-scan on beam 4

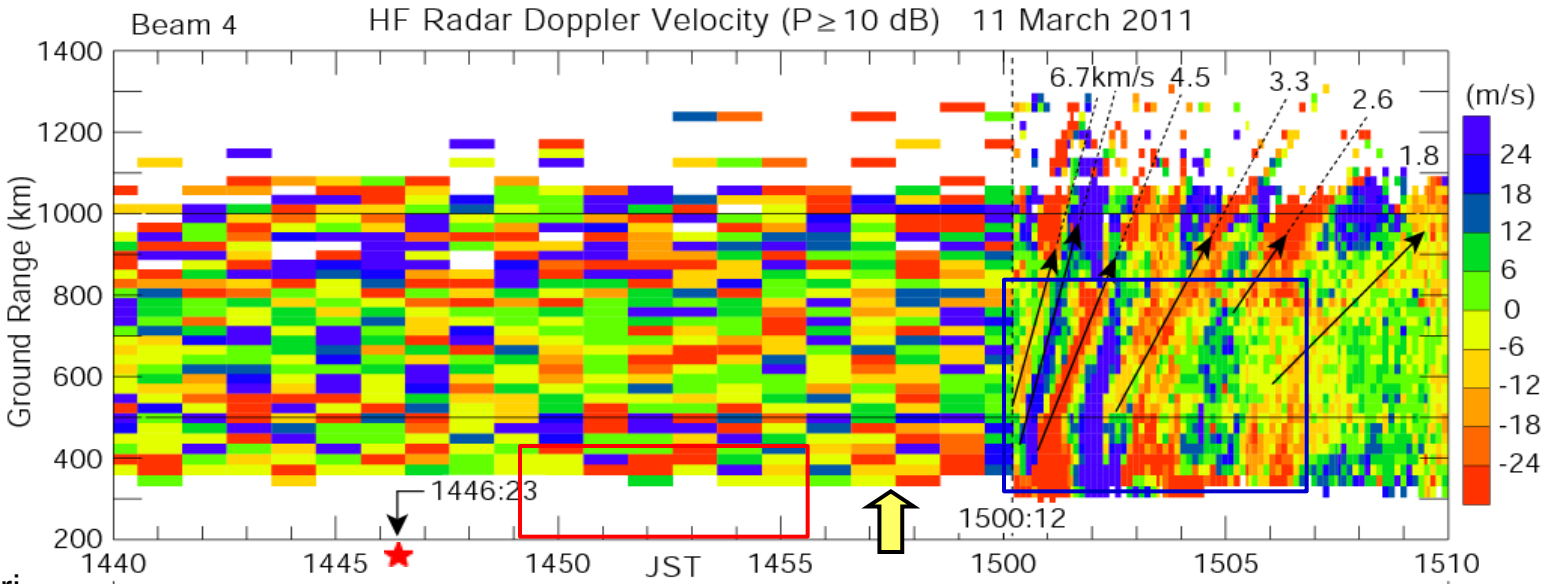
- The scan started at 1500:12 JST on 11 March.
- Beam scan sequence
  15 - 4 - 14 - 4 - 13 - 4 - …. -3 - 4 - 2 - 4 - 1 - 4
  (Beam 0 is omitted)
- 4-s integration on each beam, and 120 s for one scan
- 8-s sampling for beam 4, and 2-min sampling for other beams



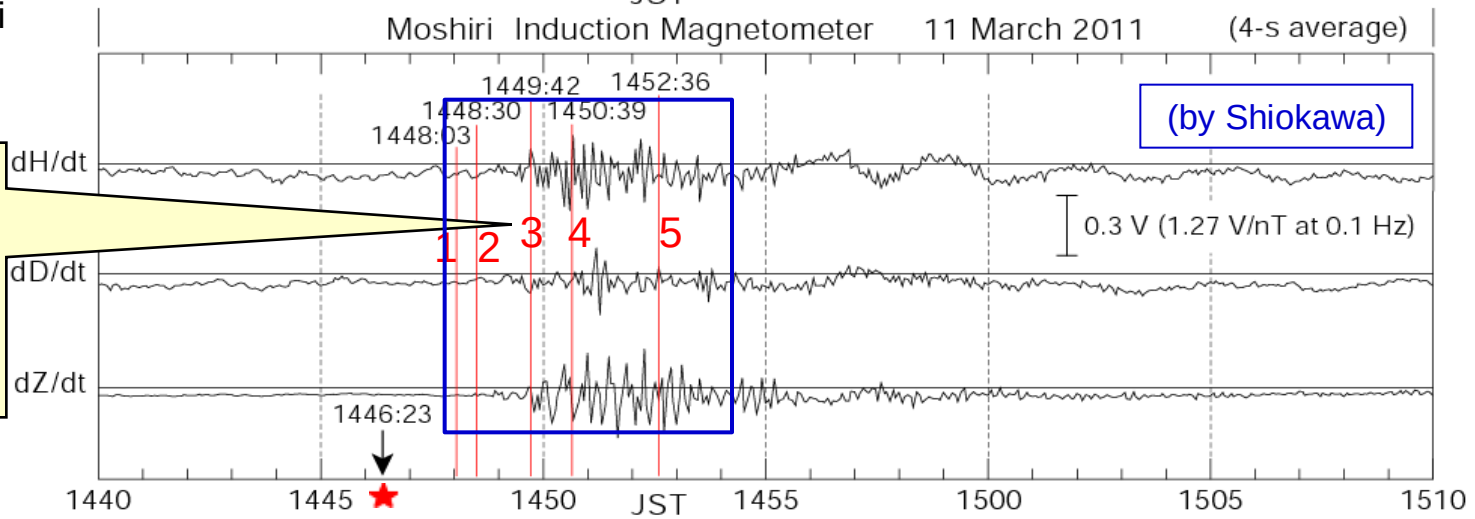
USGS Report
Occurrence : 1446:23 JST
Epicenter : 38.322°N, 142.369°E
Depth : 32 km


Beam 4
Beam 4 Echo Power (≥10 dB) 11 March 2011
Ground Range (km)
1400
1200
1000
800
600
400
200
1500:12
1446:23
1430
1500
1530
1600
1630
1700
1730
1800
1830
1900
JST
(dB)
34
28
22
16
10
Beam 4 Doppler Velocity (P ≥10 dB) 11 March 2011
(m/s)
24
12
0
-12
-24
1
2 3
4
5 6
7
Gravity waves
Oscillations with periods of 2~4 min
Northward propa-gation of Rayleigh waves (6.7~1.8 km/s)
Main- & After-shocks
M > 6 (USGS)
1. 1446:24 M9.0
2. 1508:30 M6.7
3. 1515:40 M7.9
4. 1518:50 M6.6
5. 1520:04 M6.5
6. 1525:50 M7.7
7. 1719:24 M6.5

Beam 4

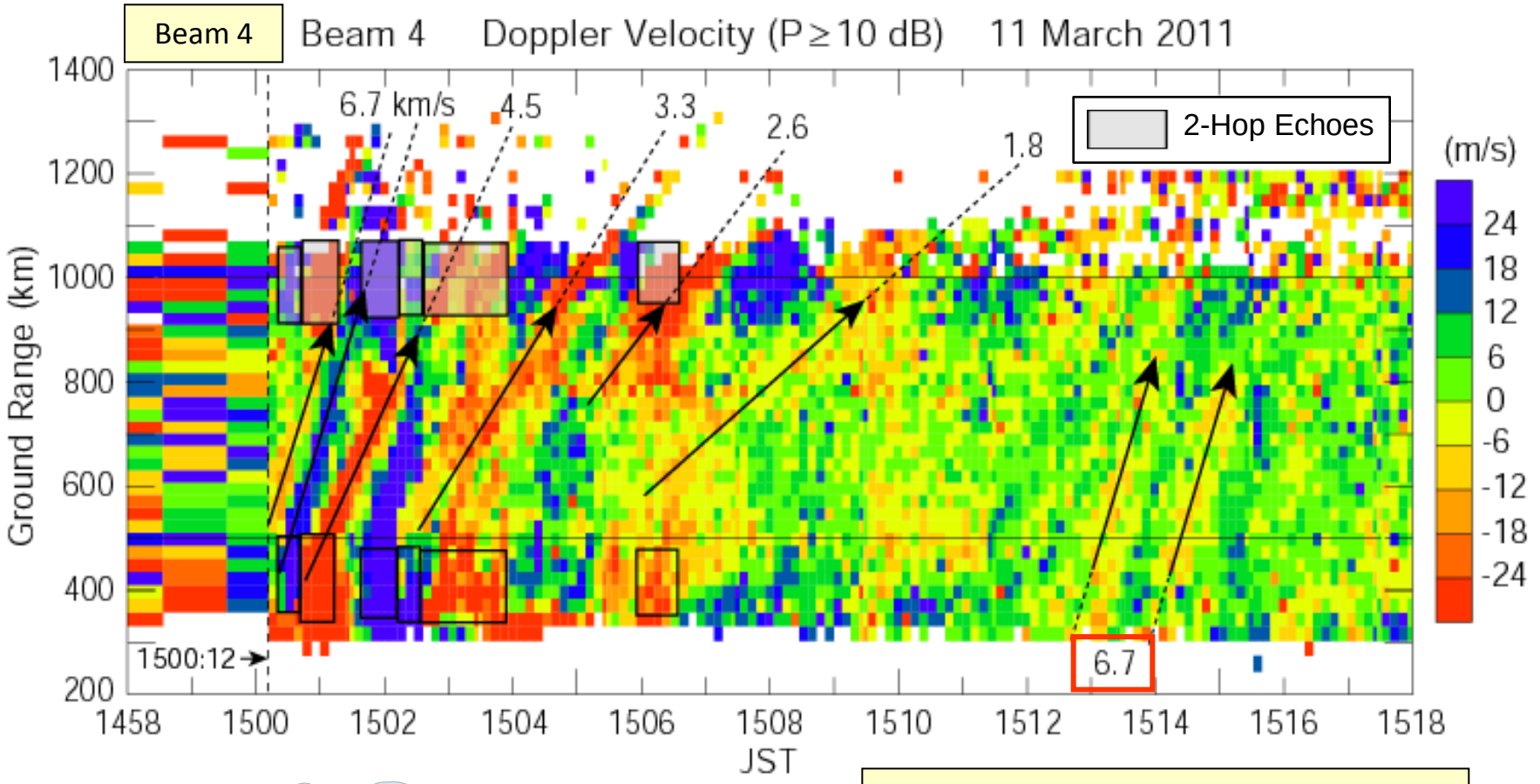


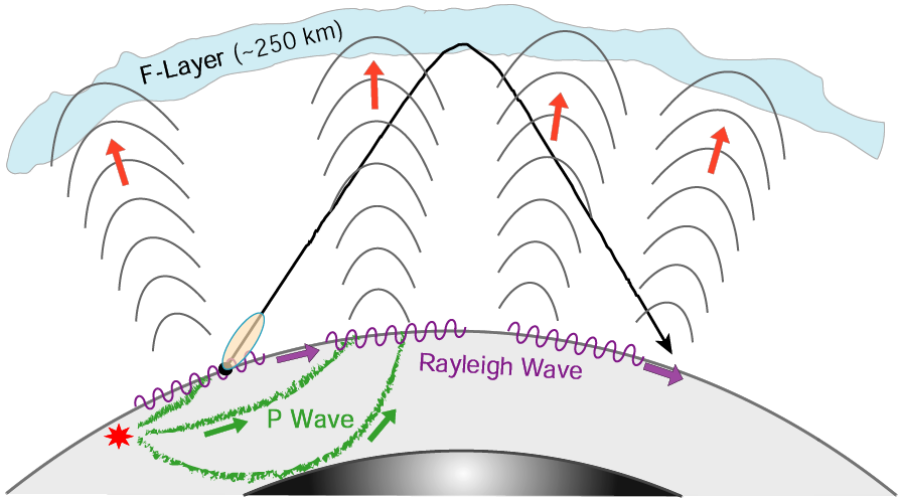
Epicenter - Moshiri
672 km



Mechanical shaking of induction magnetometer at Moshiri due to Rayleigh waves from the epicenter

- ***Velocities of Rayleigh waves from the epicenter to Moshiri*** : (1) 6.7 km/s (unclear), (2) 5.3 km/s, (3) 3.4 km/s, (4) 2.6 km/s, and (5) 1.8 km/s.
- The Rayleigh waves arrived at a radar ground range of 400 km during 1448:52 - 1455:39 JST.
- First upward-launched acoustic waves arrived at the F-region altitudes (~250 km) at around 1457 - 1458 JST to initiate the first ionospheric disturbances with 6.7 km/s.
- Rayleigh wave disturbances lasted for about 7 min at Moshiri and in the Doppler velocity data.



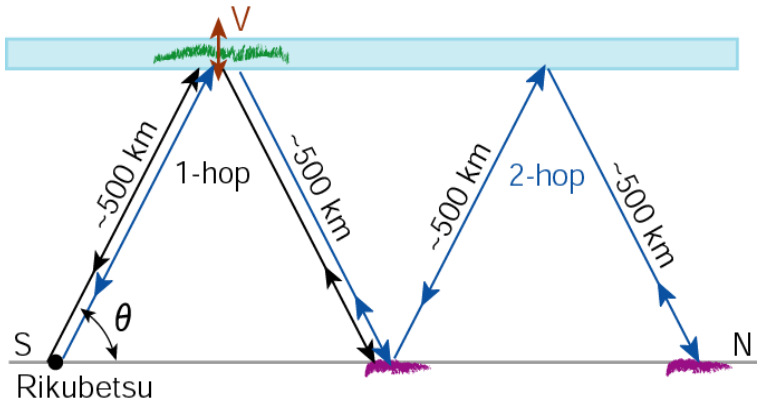


Northward propagation of disturbances

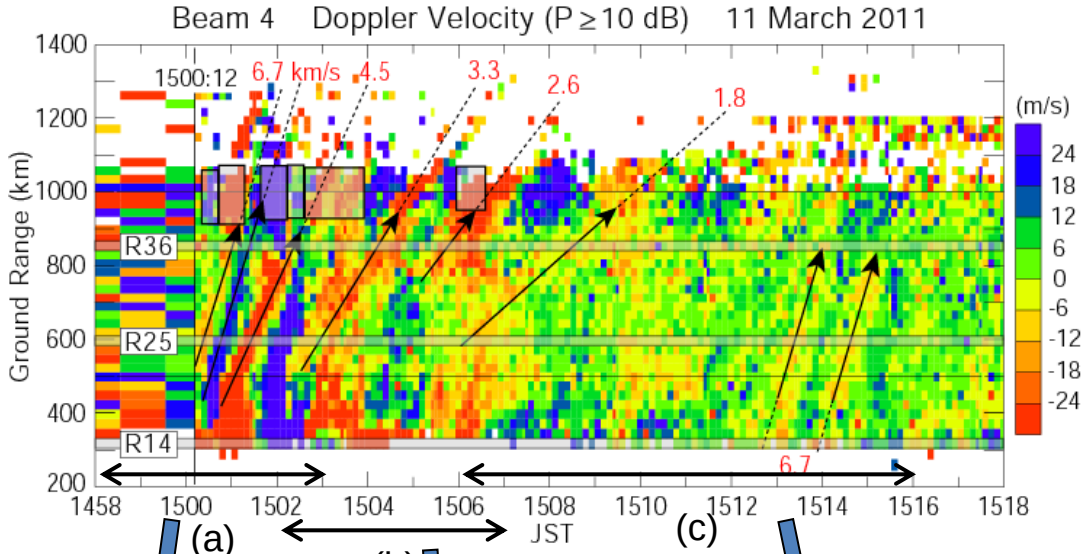
- Rayleigh waves at 6.7 - 1.8 km/s with a velocity dispersion
- Velocities of 4.5 ~ 1.8 km/s are consistent with those derived from the Moshiri induction magnetometer.
- Signature of 6.7 km/s is unclear in the Moshiri data.

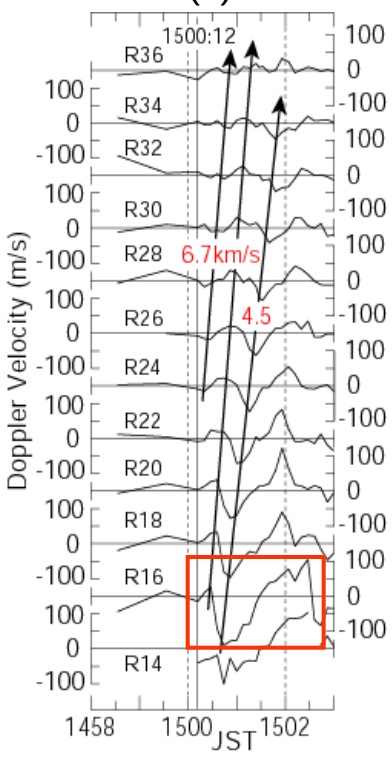
Acoustic waves excited by the Rayleigh waves propagated upward to induce up-down motions of the F-region plasma.

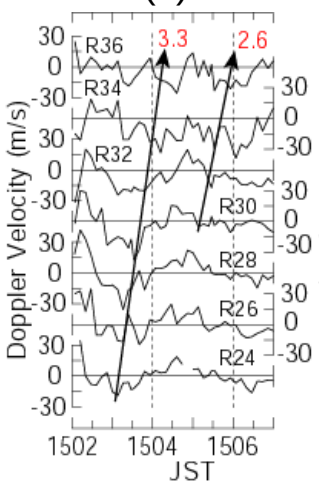
Contaminated by 2-hop propagation

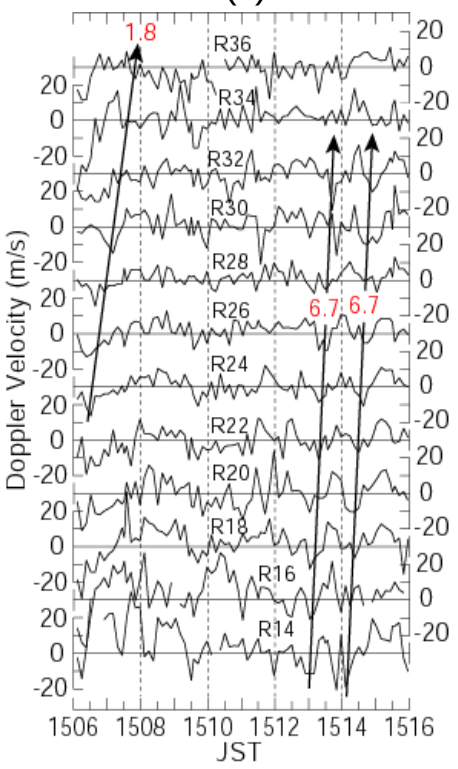


$V_{obs} = 2V\sin\theta$



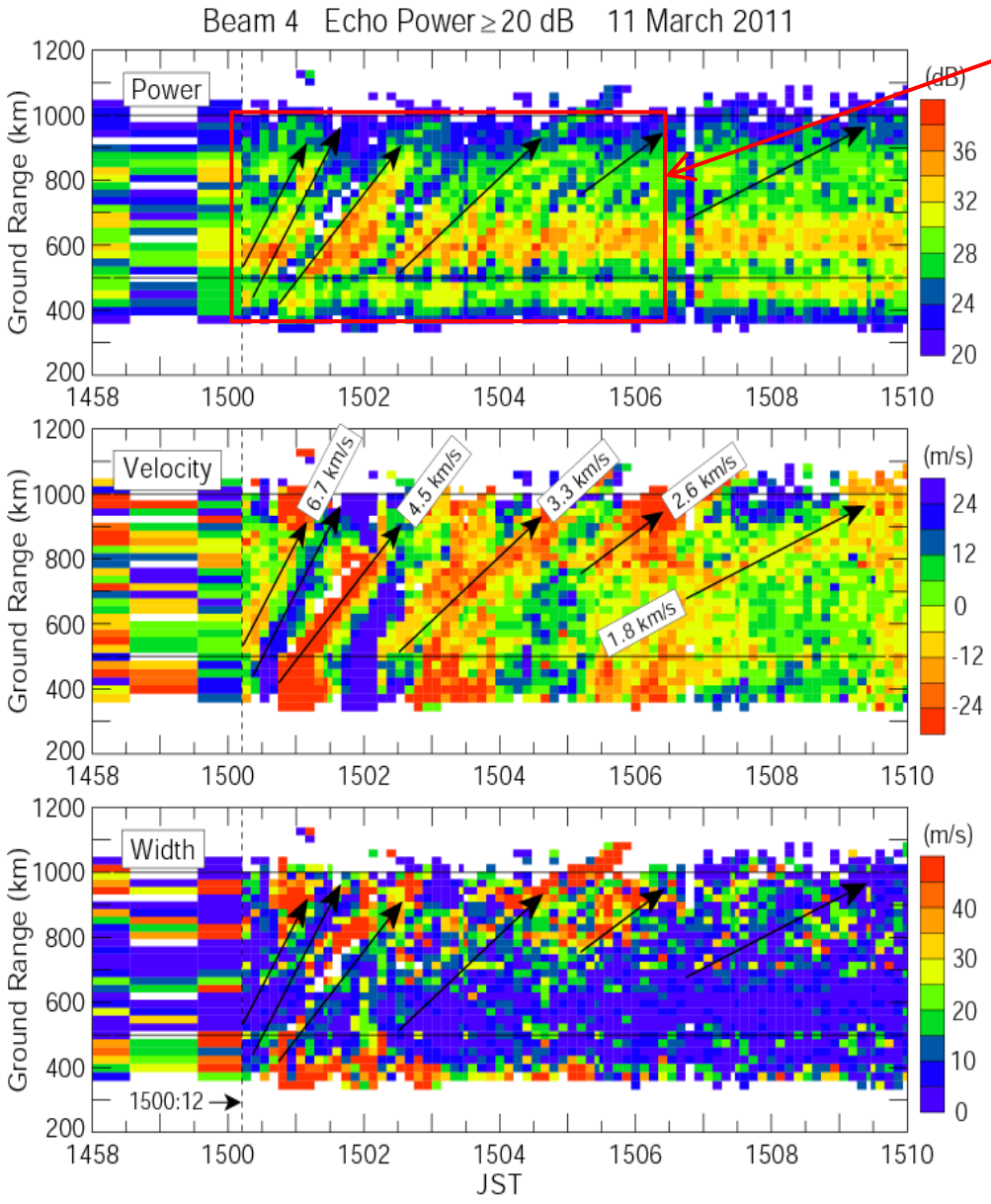




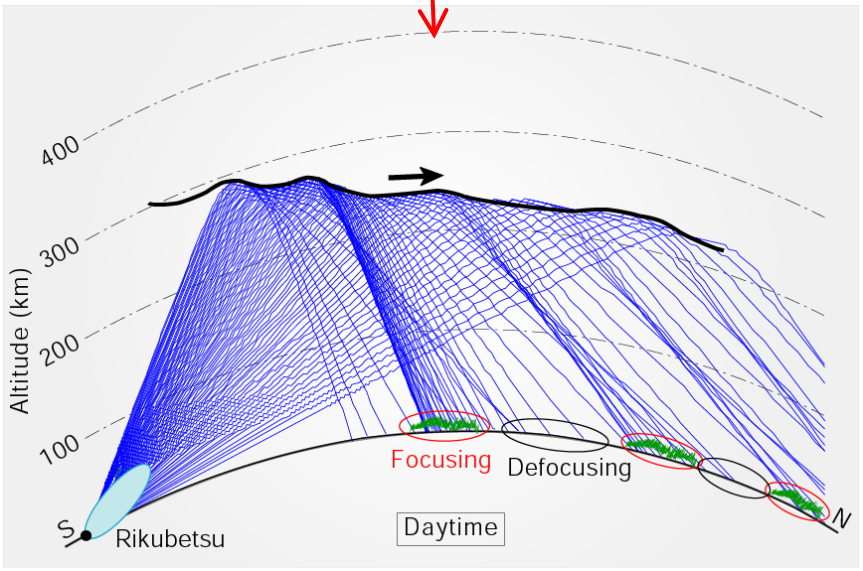


- Doppler velocity oscillations with periods of 1 - 2 min, in line with past observations using HF-Doppler sounding technique
- Maximum of observed Doppler velocity (V_{obs}) during 1500 – 1503 JST is ±100 m/s at near ranges, and decreases with range even if V is constant, according to the above $V_{obs} = 2V\sin\theta$. V_{obs} decrease with time.

Beam 4



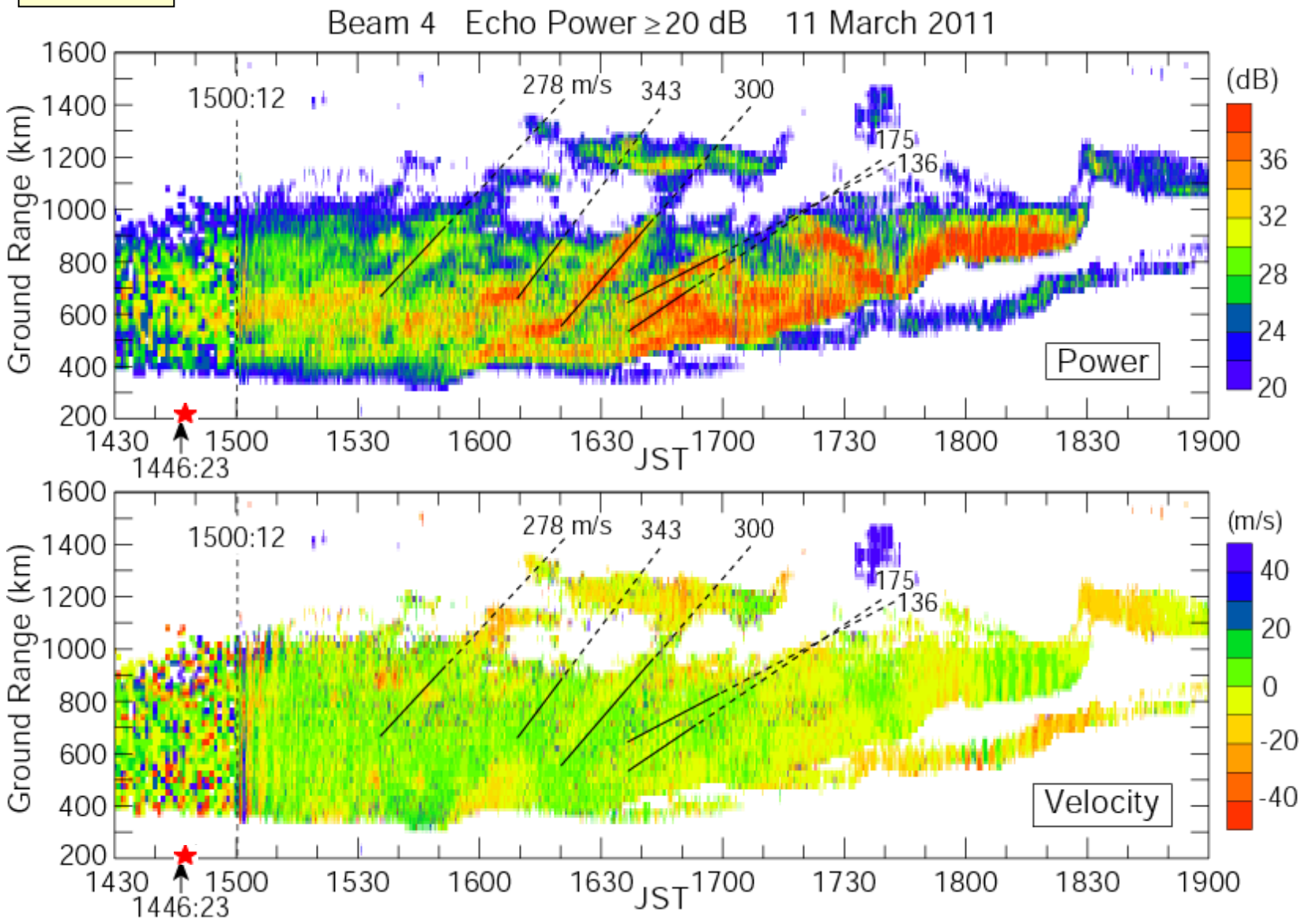
Increase (decrease) of echo power due to focusing (defocusing) of radar waves



- Echo power, velocity, and spectral width oscillations with periods of 1- 2 min
- Also echo power oscillations with a period of 30 s
- Most of spectral widths are less than 10 m/s.
- No clear correlations among three parameters

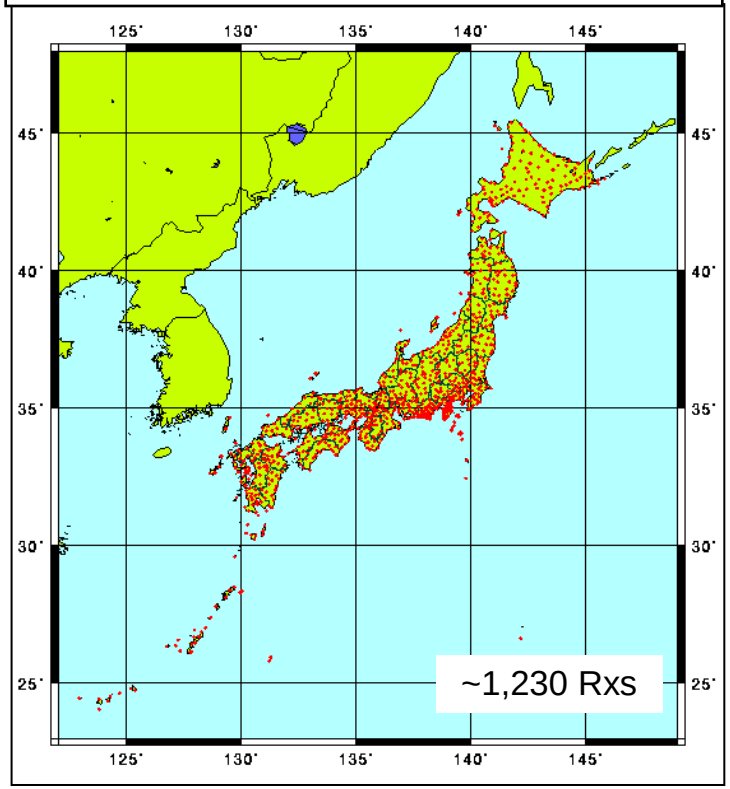
Beam 4

Atmospheric Gravity Waves (AGW)

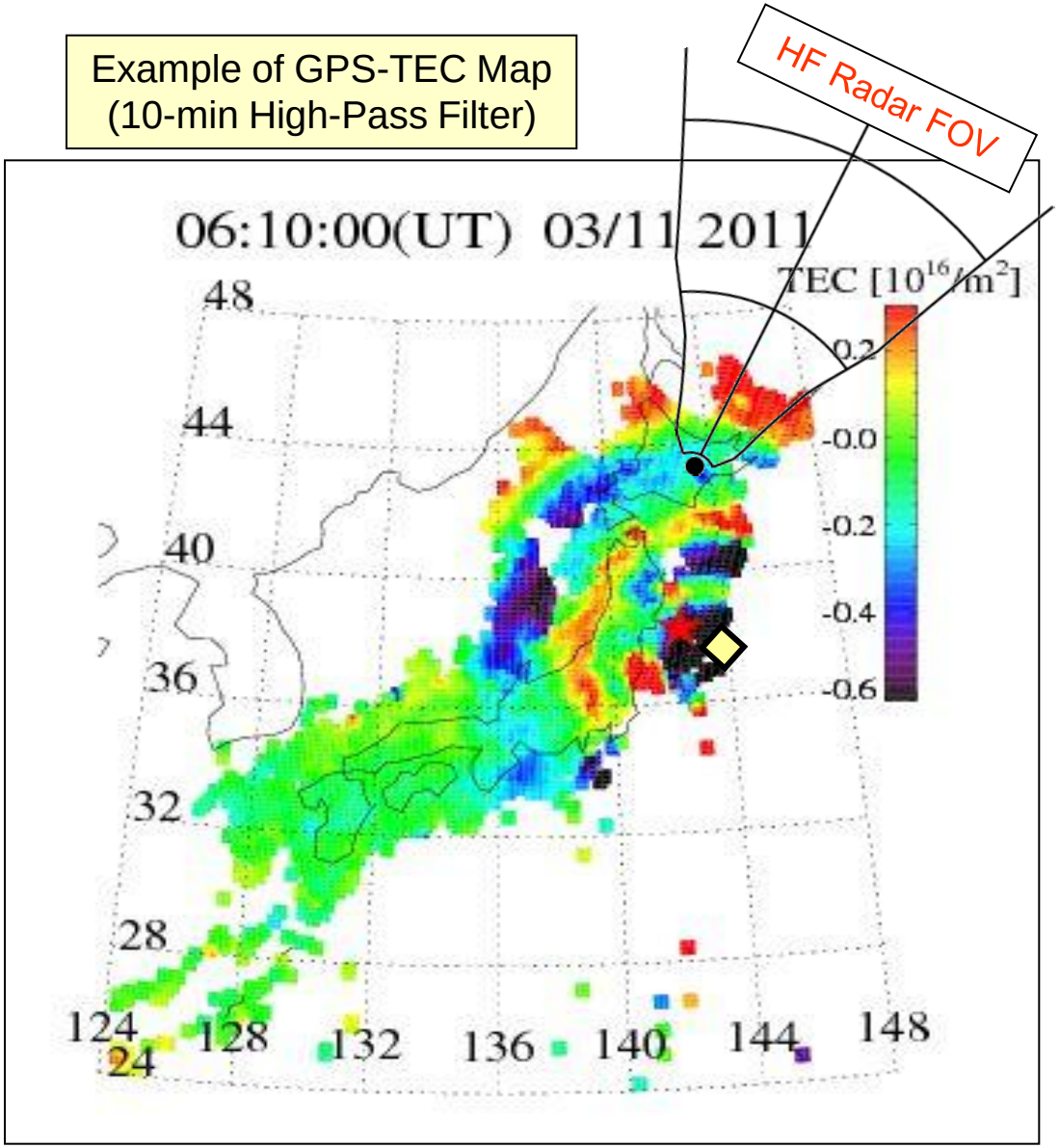


Northward propagation (140 - 350 m/s) of AGW are more clearly seen in Echo Power because of focusing/defocusing of radar waves

GPS Receiver Array Network (GEONET) to obtain TEC map over Japan



Example of GPS-TEC Map (10-min High-Pass Filter)



Epicenter (38.32°N, 142.37°E)

Ionospheric Epicenter (37.5°N, 144.0°E), 170 km SE from the epicenter, from which large-scale, circular wavefronts expand radially with time.

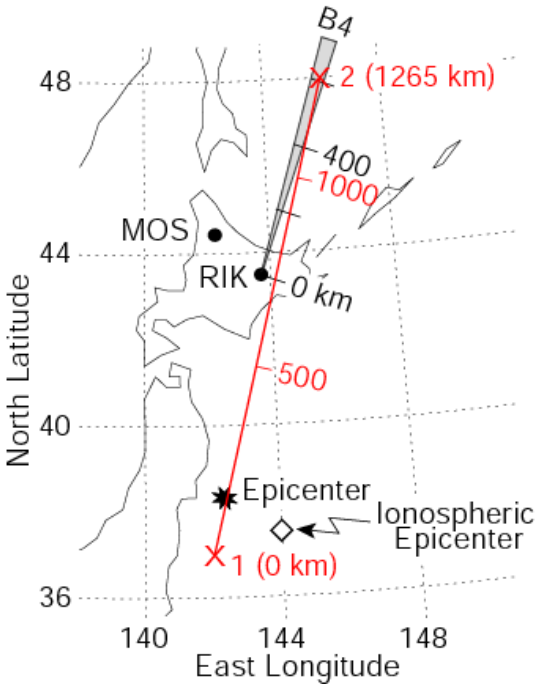
Movie of GPS-TEC Map

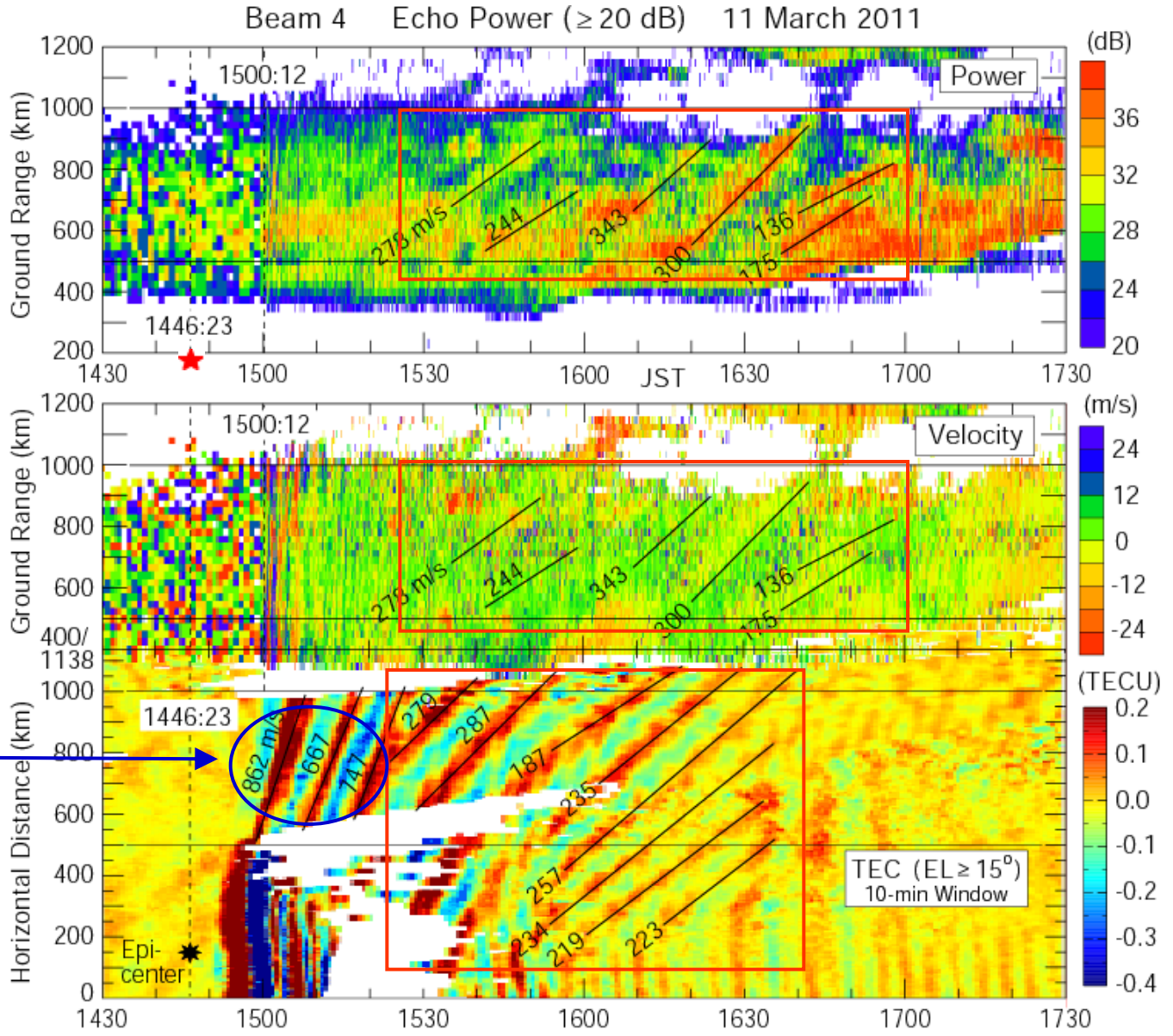
(http://www.seg.nict.go.lp/2011TohokuEarthquake)

(Tsugawa et al., 2011)

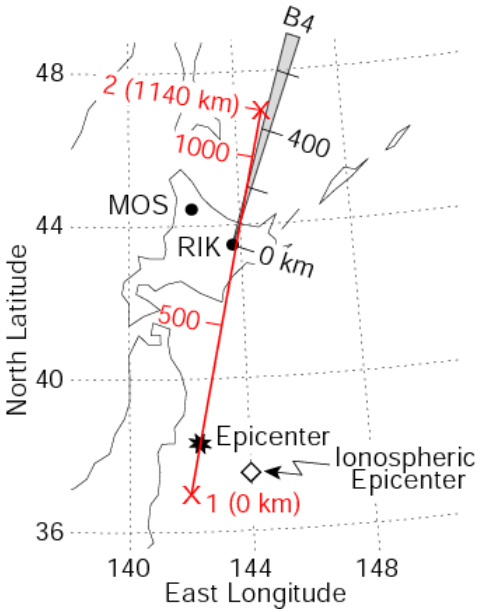
- 0500 – 0900 UT (1400 – 1800 JST)
- Time resolution : 30 s
- Satellite elevation angles $\geqq 15^{o}$
- Earthquake : 0546:23 UT (1446:23 JST)
- Start of ionospheric disturbances : ~0550 UT (~1450 JST)

- Gravity waves propagation from the epicenter
- Waves are more clearly seen in Echo Power, suggesting focusing / defocusing of the radar waves.

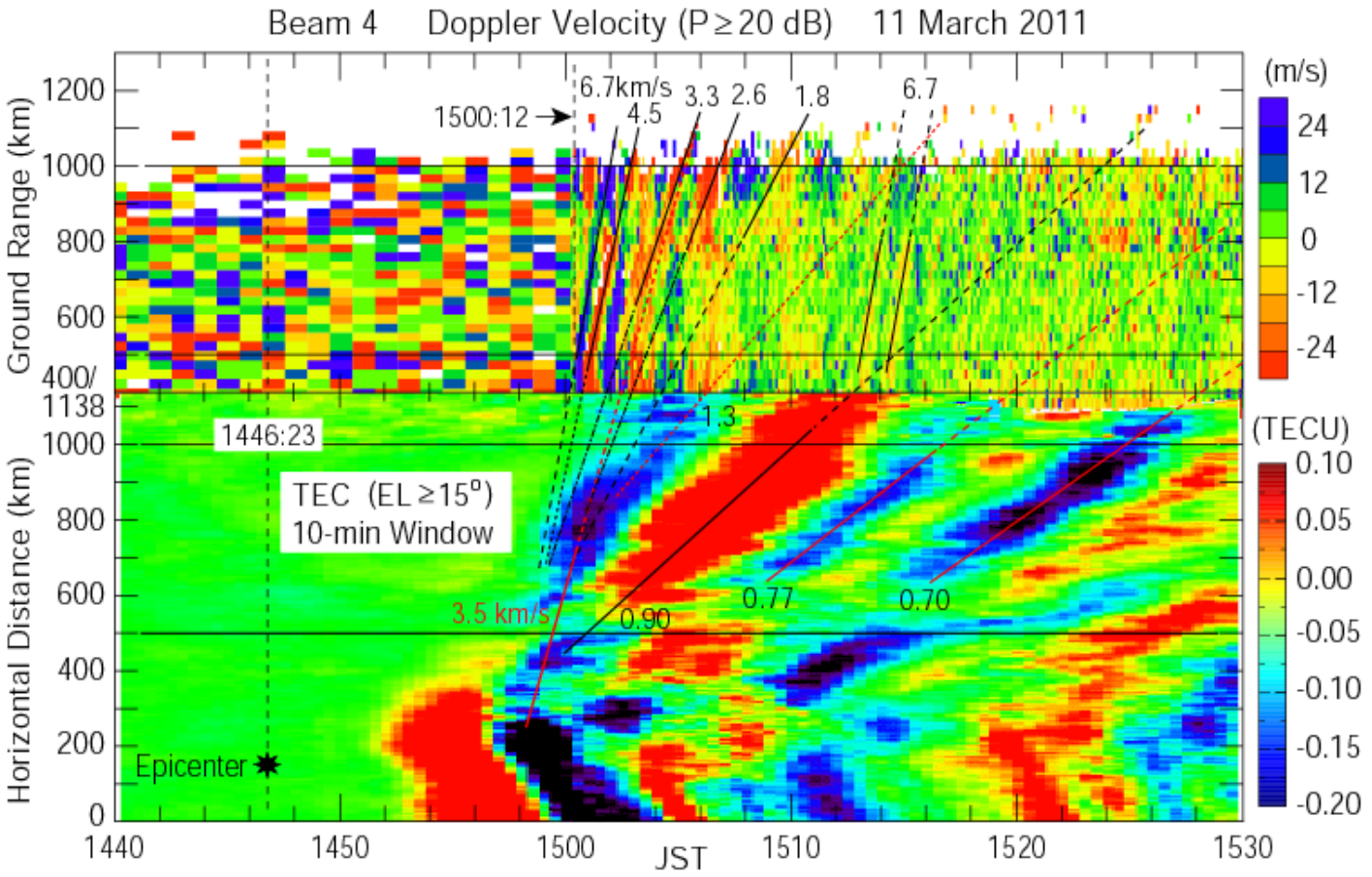


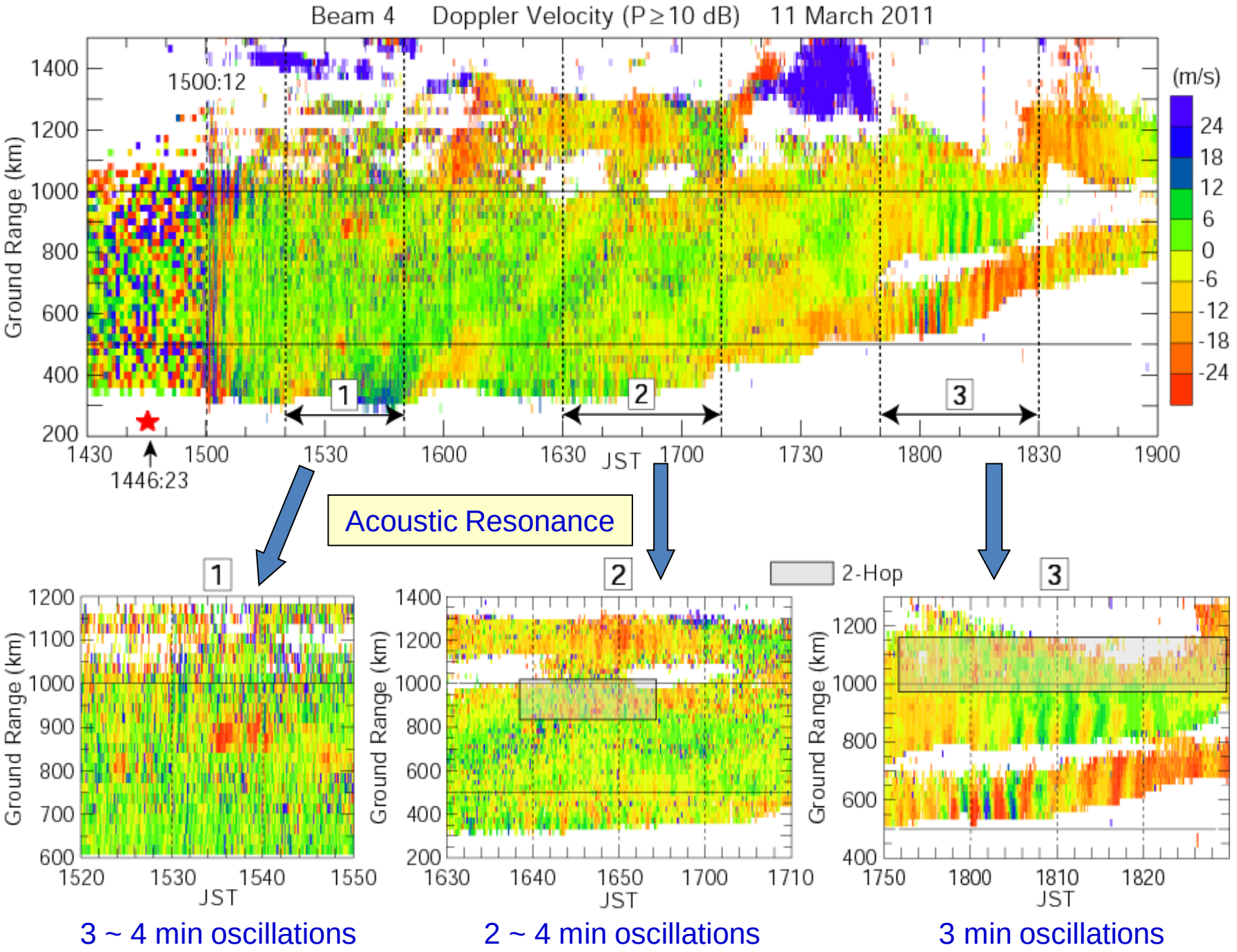


Acoustic waves (750 - 860 m/s) from the epicenter (no such signatures in echo power and Doppler)

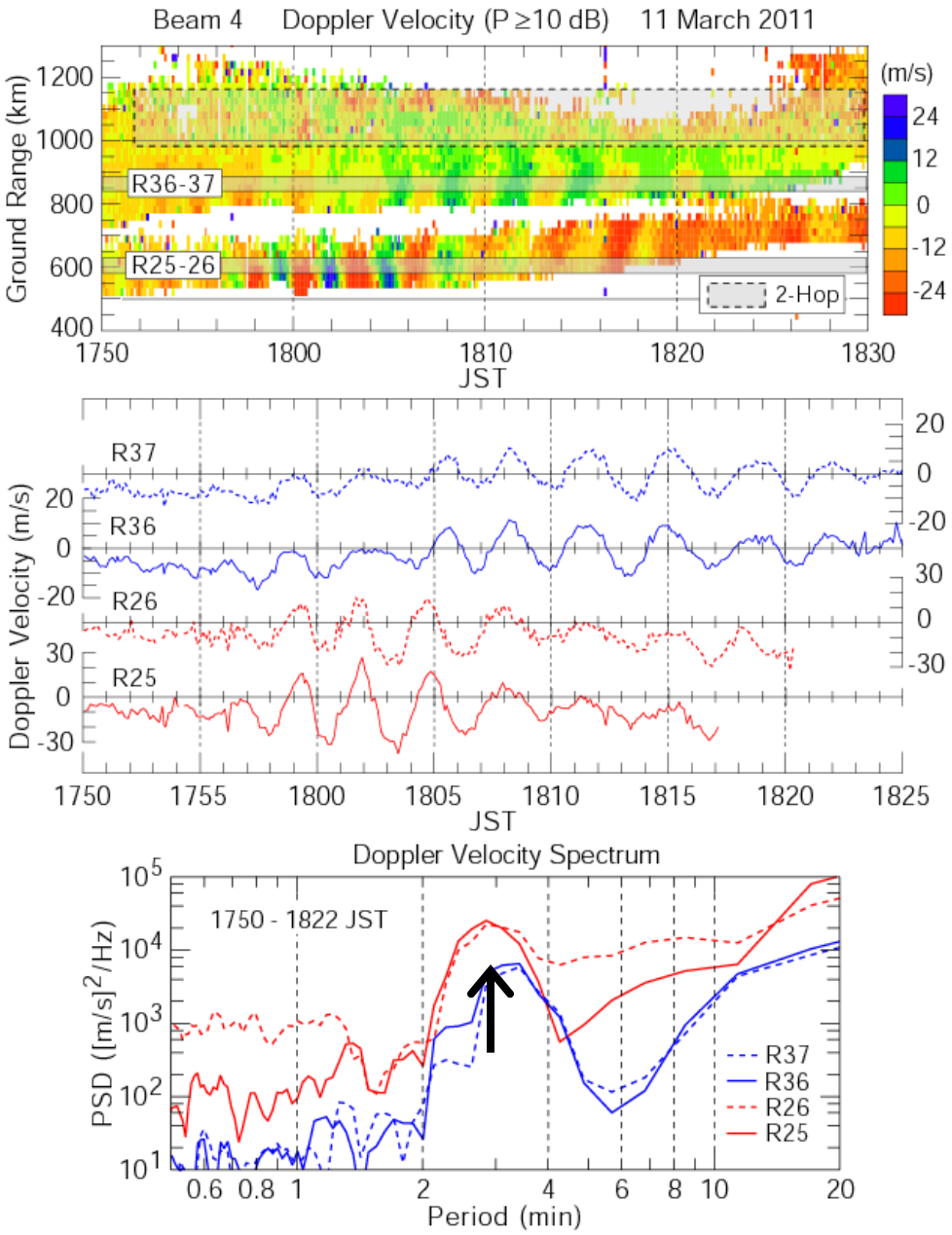


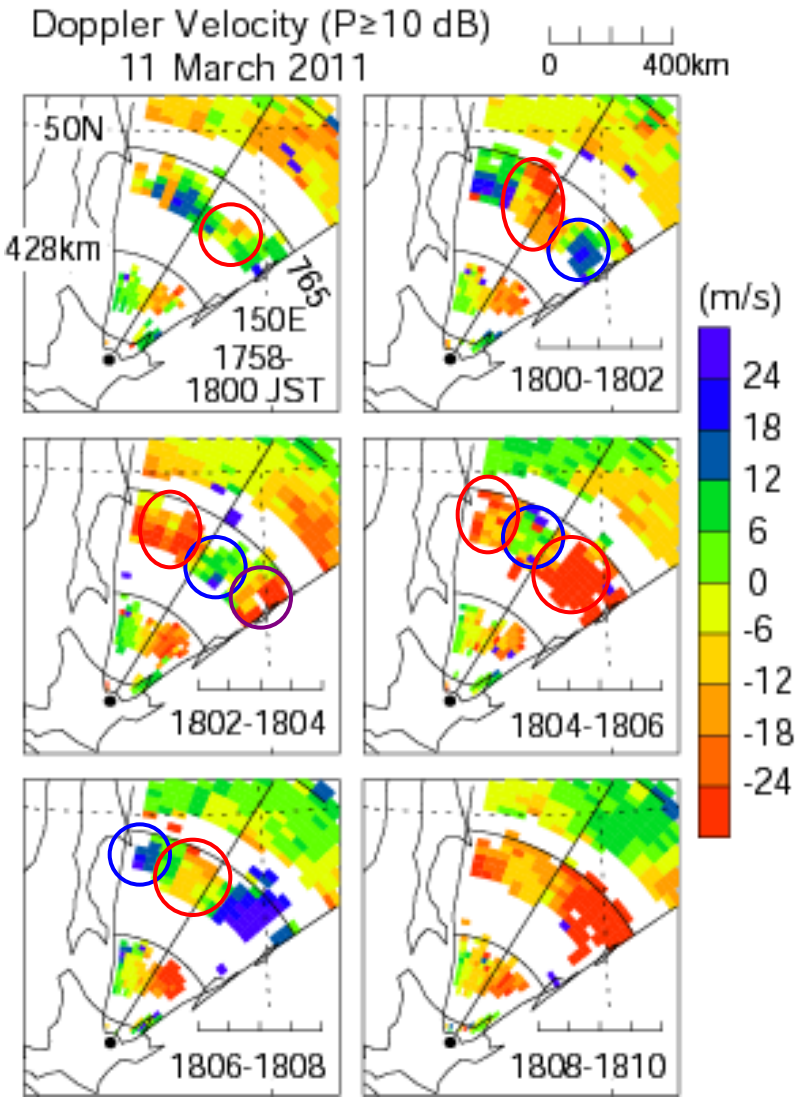
- 6.7, 4.5, 3.3 and 2.6 km/s wave propagations seen in Doppler have no counterparts in TEC.
- 1.8 km/s in both Doppler and TEC
- Acoustic-wave propagations from the epicenter with 1300, 900, 770, 700 m/s are not clear in Doppler, suggesting that these acoustic waves dissipated before arriving within the radar FOV.



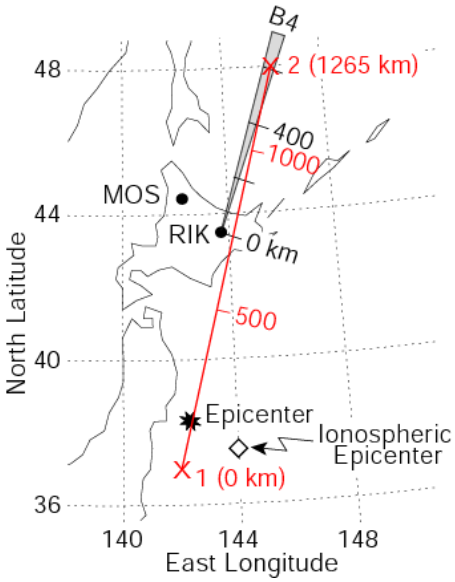

Beam 4 Doppler Velocity (P≥10 dB) 11 March 2011
Ground Range (km)
1500:12
1446:23
JST
(m/s)
24
18
12
6
0
-6
-12
-18
-24
1
2
3
Acoustic Resonance
2-Hop
3 ~ 4 min oscillations
2 ~ 4 min oscillations
3 min oscillations

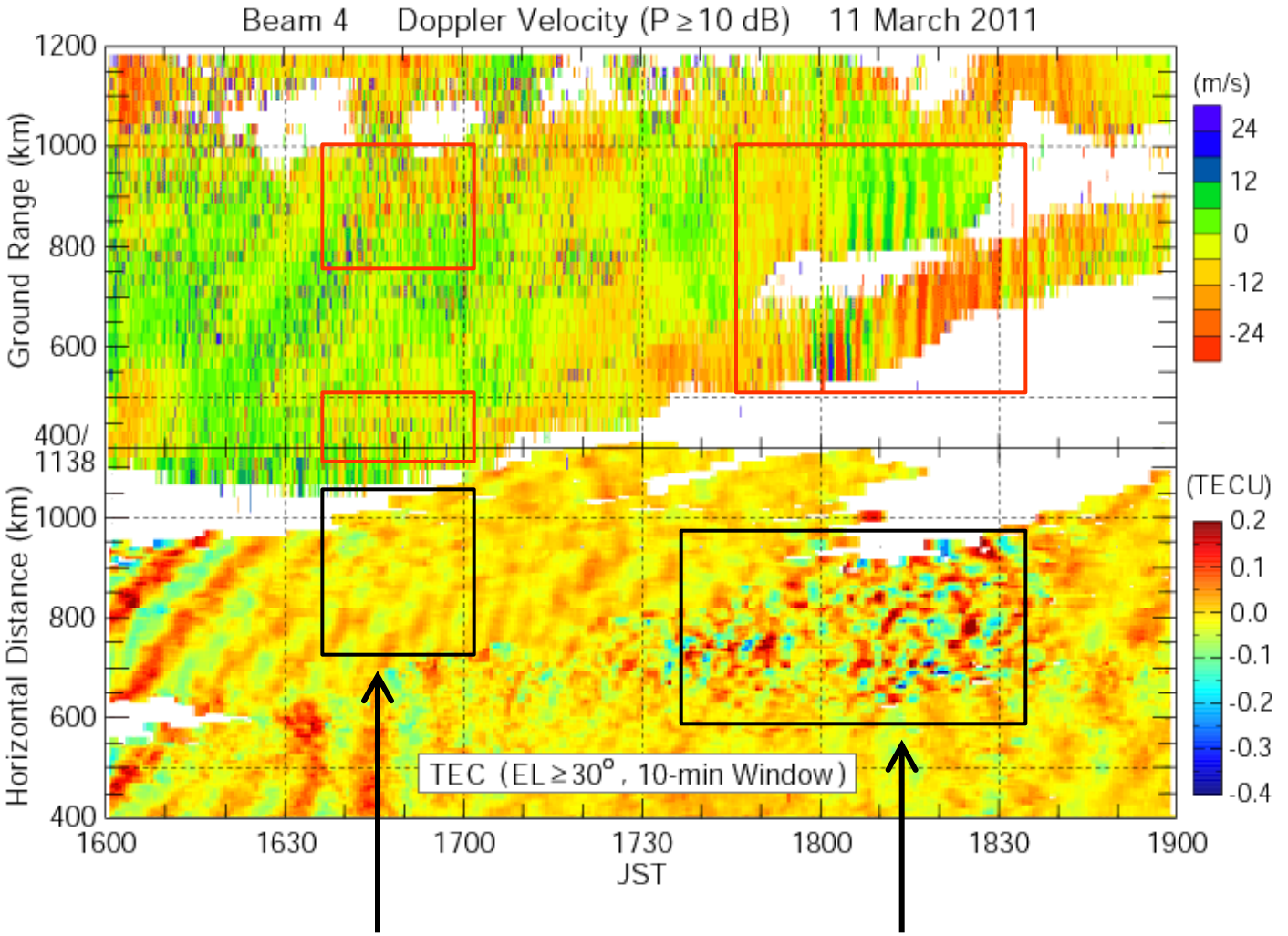
3 min Oscillations





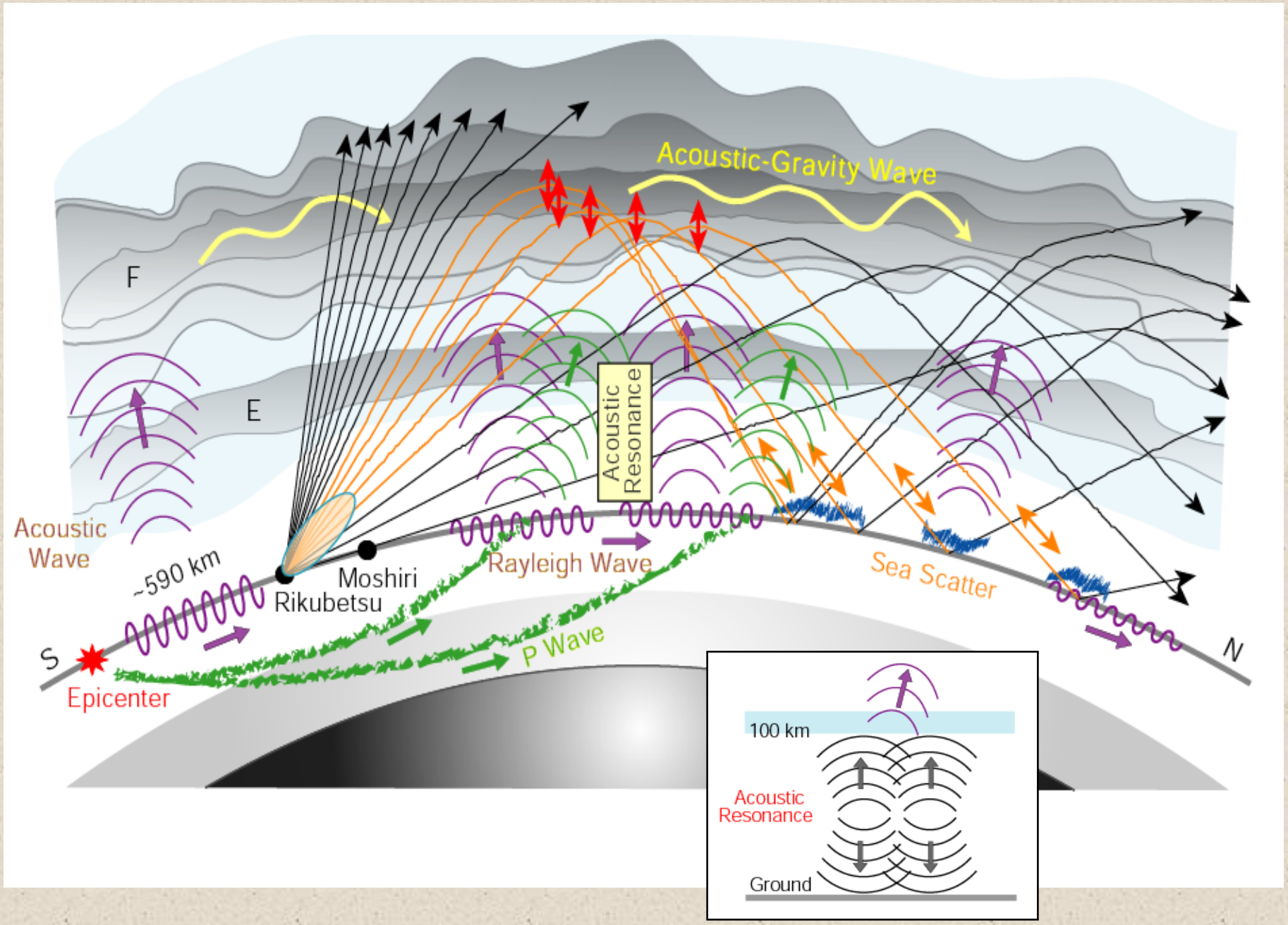
Structures with an E-W wavelength of ~400 km move westward at ~1.6 km/s. Also time-varying wavy structures along N-S.





2 ~ 4 min oscillations

3 min oscillations


Acoustic-Gravity Wave
F
E
Acoustic Resonance
Acoustic Wave
~590 km
Moshiri
Rikubetsu
Rayleigh Wave
Sea Scatter
S
N
Epicenter
P Wave
100 km
Acoustic Resonance
Ground

Summary

- Huge ionospheric disturbances over the Sea of Okhotsk after the 2011 Tohoku earthquake (M_w=9.0) were detected with the SuperDARN Hokkaido radar. Thanks for accidental and lucky THEMIS-scan operation.
- Rayleigh waves (6.7 ~ 1.8 km/s) propagated northward from the epicenter while launching upward-propagating acoustic waves. 8 ~ 9 min later, the acoustic waves arrived in the F-region to induce up-down motions of the plasma.
- Past observations showed ionospheric disturbances caused by Rayleigh waves at 3.5 ~ 3.9 km/s. In addition to these velocities, current observations first found faster Rayleigh waves at 4.5 ~ 6.7 km/s.
- The radar also detected northward-propagating atmospheric gravity waves (AGW) with velocities less than 350 m/s, and oscillations with periods of 2 ~ 4 min caused by the acoustic resonance between the ground surface and the lower thermosphere. This resonance and AGW were also observed in GPS-TEC data.
- Correspondence between the radar and TEC observations are not so good. In particular, fast northward-propagating Rayleigh waves are indiscernible in TEC data. One reason may be due to the difference in the observation technique.