Concentric traveling ionosphere disturbances triggered by Super Typhoon Meranti

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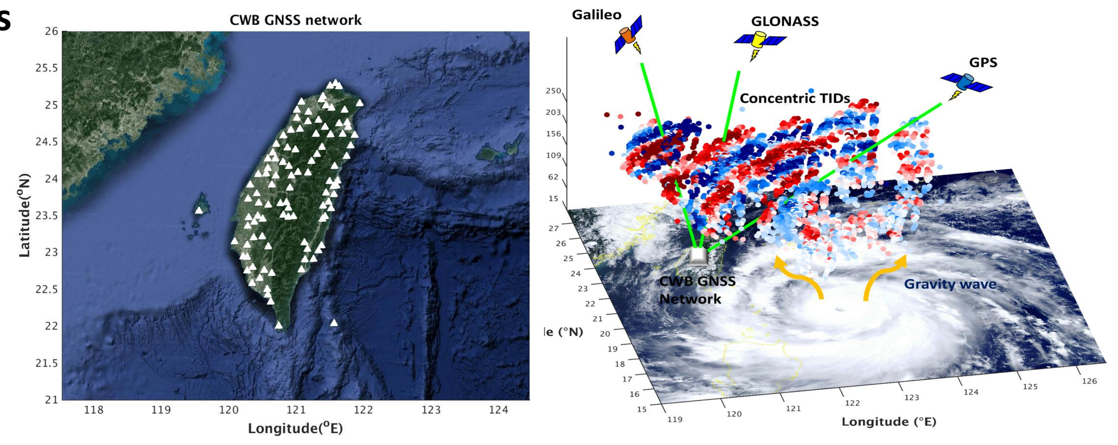
Introduction

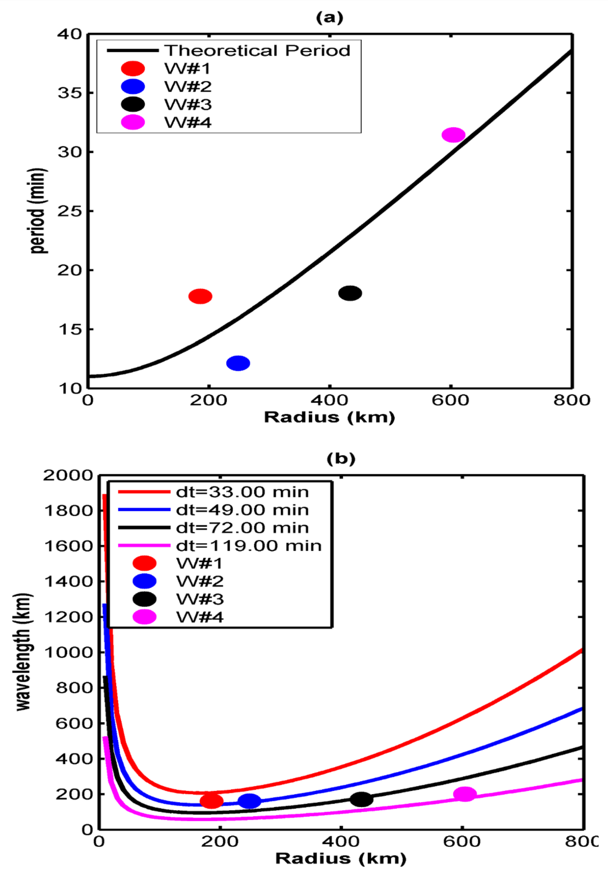
- Deep convection is considered to be the important sources of gravity waves (GWs) in the troposphere.
- Typhoons are tropical cyclones that are accompanied by a large low-pressure center and numerous convective cells.
- The typhoon-induced concentric GWs (CGWs) in the middle atmosphere were observed by using ground-based all-sky imagers and joint spaceborne satellites.
- There is no direct observational evidence of typhoon-induced CGWs in the ionosphere, especially in the low-latitude region where the electron density is large around equatorial ionization anomaly crests.
- We present the first observation of the typhoon-induced dispersive CTIDs by using ground-based Global Navigation Satellite Systems (GNSS) network when the Super Typhoon Meranti approaching Taiwan on 13 September 2016.

Dataset and Methodology



- The total electron content (TEC) derived from ground-based GNSS array of Central Weather Bureau in Taiwan.
- The ionosphere height for converting slant to vertical TEC is adjusted to 250 km altitude.
- Hilbert-Huang transform (HHT) analysis.
- Five order Butterworth filter.

Boussinesq Dispersion Relation



In the case of no background wind, the dispersion relation is given by [*Hines*, 1960].

$$\omega^2 = \frac{N^2 k^2}{k^2+m^2} = N^2 \cos^2\beta \quad (1)$$

The buoyancy frequency N is estimated to be $2\pi/11\ \mathrm{min}^{-1}$ at the 250 km ionosphere height. Here we assumed the CGWs launched from upper troposphere near ~12 km altitudes and propagated to the ionosphere near 250 km altitudes, the vertical distance Δz is 238 km . Using the relation $\tan\beta = \frac{R}{\Delta z}$, where R indicate the horizontal radius traveled by the CGWs, and equation (1), the theoretical GWs periods ω_g can be expressed in terms of R as

$$\omega_g = \frac{2\pi}{N\cos\beta} = \frac{2\pi}{N}\sqrt{1+\frac{R^2}{\Delta z^2}} \quad (2)$$

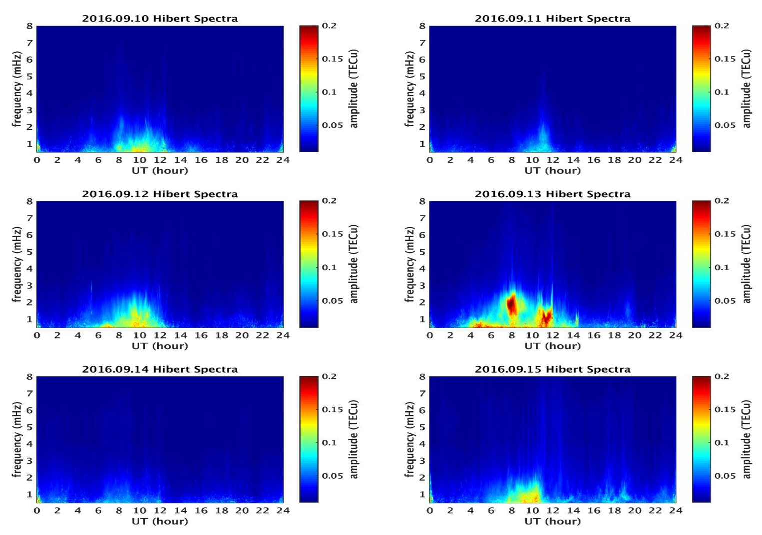
Additionally, the vertical group velocity in this case is considered,

$$c_g = \frac{\Delta z}{\Delta t} = -\frac{Nkm}{(k^2+m^2)^{\frac{3}{2}}} = -\frac{N}{k}\cos^2\beta\sin\beta \quad (3)$$

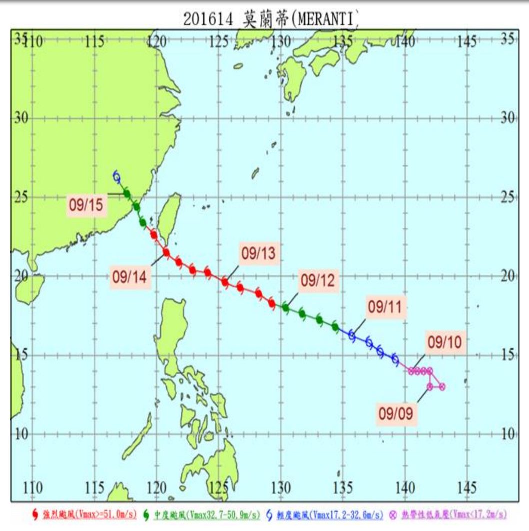
Using equation (3), the theoretical horizontal wavelength λ_h of GWs as a function of horizontal radius and vertical propagation time is given.

$$\lambda_h = \frac{2\pi R^2 (1+\Delta z^2/R^2)^{3/2}}{N \Delta z \Delta t} \quad (4)$$

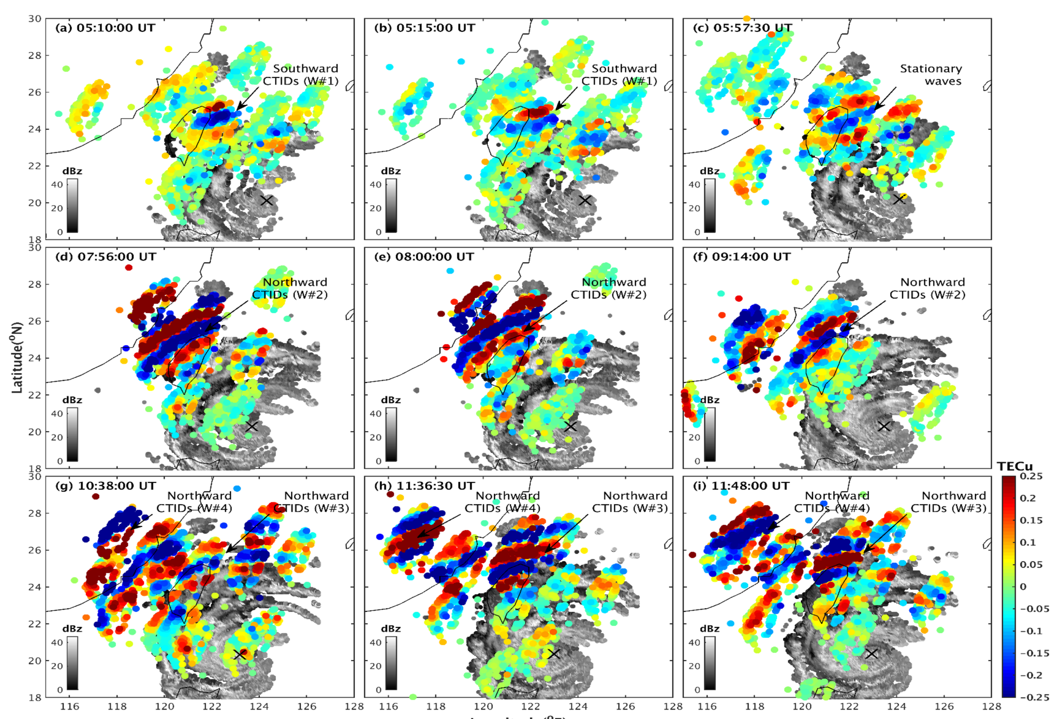
Hilbert Spectra Analysis



- The Hilbert spectra analysis of the GNSS TEC during the period of typhoon approaching on 10–15 September 2016.
- Two pronounced enhancements of wave amplitudes on 13 September
  - ~8–12 min (07:00–09:00 UT)
  - ~12–20 min (10:00–12:00 UT)



Concentric Traveling Ionosphere Disturbances

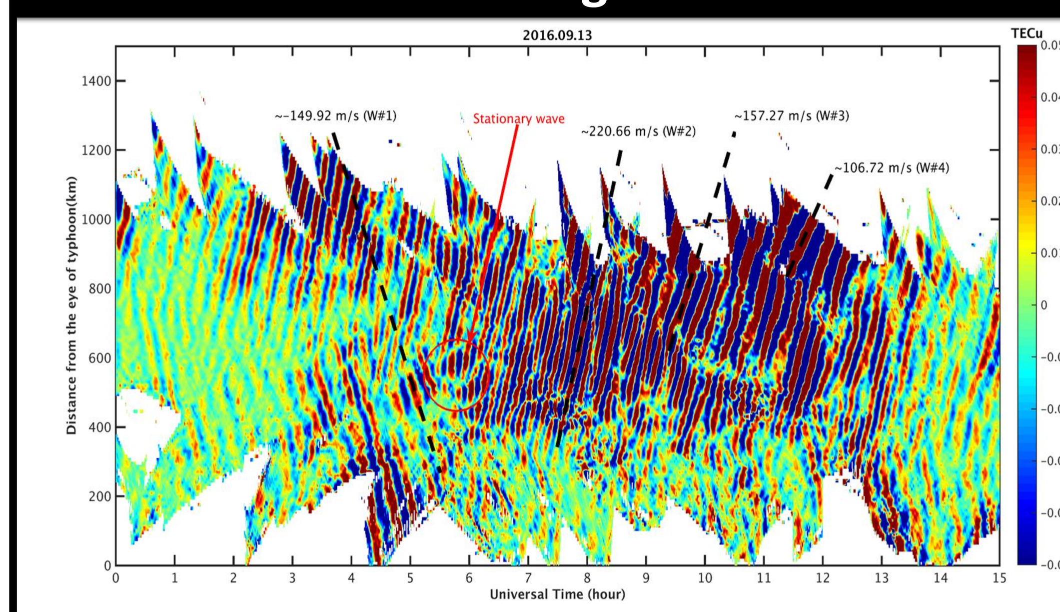


- The combined filtered TEC maps with the weather radar reflectivity during 05:10-11:48 UT.

	W#1	W#2	W#3	W#4
Wavelength	160 km	160 km	170 km	200 km
Amplitude	0.2 TECU	0.3 TECU	0.8 TECU	0.8 TECU

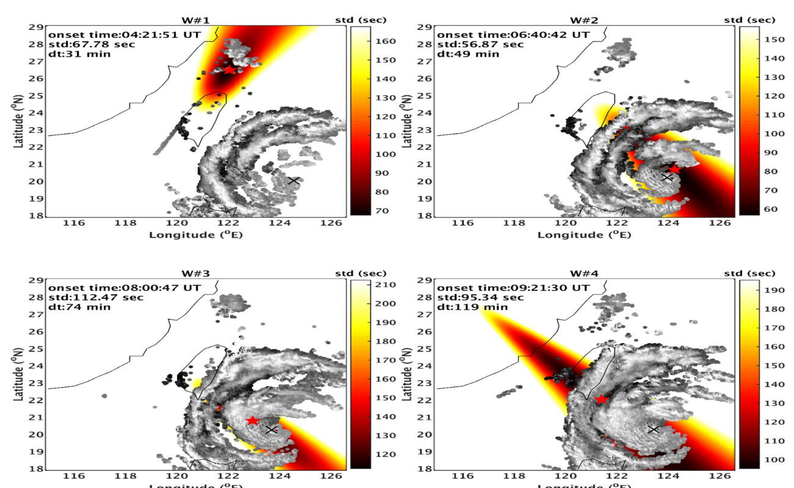
- These CTIDs propagated ~1200 km in northward direction for more 10 hours and excited broader scales after the typhoon impinged on rugged terrain of Taiwan at ~09:00 UT.

Travel Time Diagram of CTIDs



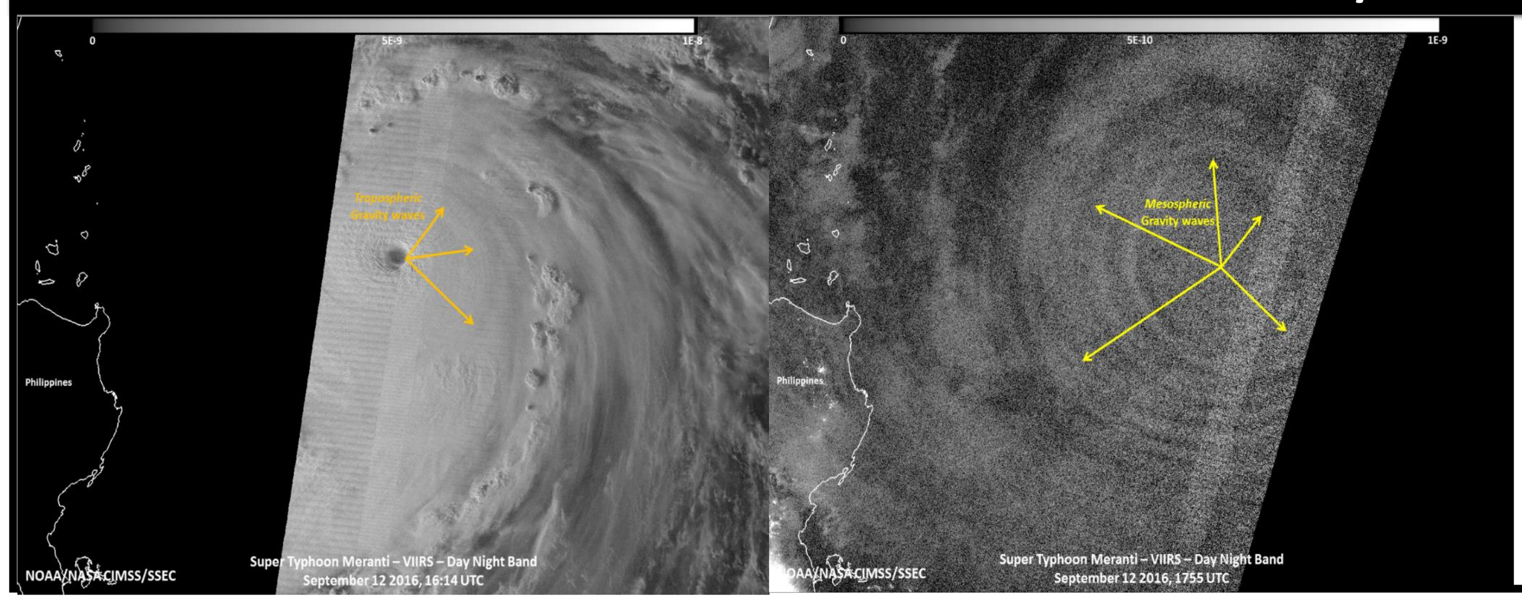
The CTIDs display various wave characteristics with propagation velocities of ~106-220 m/s and periods of ~8-30 min.

Search CTIDs Origin



The ray-tracing technique is applied to search the CTIDs origins. The optimal sources (red star) of the wave trains are suggested to be related to the convective clouds in northern Taiwan(W#1), the spiral rainbands (W#4), and the eyewall (W#2 and W#3) of the typhoon, respectively.

Suomi NPP Satellite VIIRS/DNB



The Suomi NPP satellite VIIR/DNB observed visible CGWs patterns in the mesopause OH airglow around Philippine Sea a day before GNSS observations over Taiwan. The DNB images show small- and medium-scale CGWs with horizontal wavelengths of ~40-50 km near the typhoon eye and of ~130~200 km in the outer ring of CGWs.

Discussion and Conclusion

- We report the first evidence of typhoon induced dispersive CTIDs using ground-based GNSS network in Taiwan during super typhoon Meranti on 13 September 2016..
- The multiple CTIDs are most likely triggered by the convective clouds, spiral rainbands and the eyewall of typhoon induced CGWs. The weak background winds in equinoctial seasons providing a favorable condition for typhoon-induced CGWs to propagate upward.
- The CTIDs agree with theoretical dispersion relation suggesting that the CTIDs were associated with the primary CGWs propagating directly from the troposphere, instead of secondary gravity waves excited from the breaking primary wave.
- The CTIDs lasted for more than 10 hours since the convective cells inside the typhoon could excite CGWs for many hours.
- The stationary TIDs are most likely related to the interference between the convective clouds-generated CTIDs and typhoon-induced CTIDs.
- The Central Mountain Range in Taiwan was expected to impact Typhoon Meranti. It is speculated that the rapid loss of momentum and energy due to viscous interaction could be an additional factor in exciting GWs with broad spectra when the typhoon is near the coast or landfall.

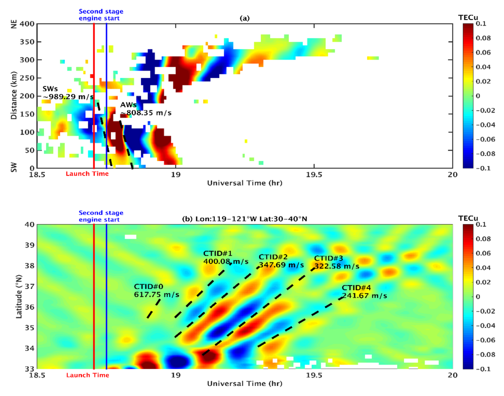
CTIDs triggered by SpaceX Falcon 9 Rocket

Introduction

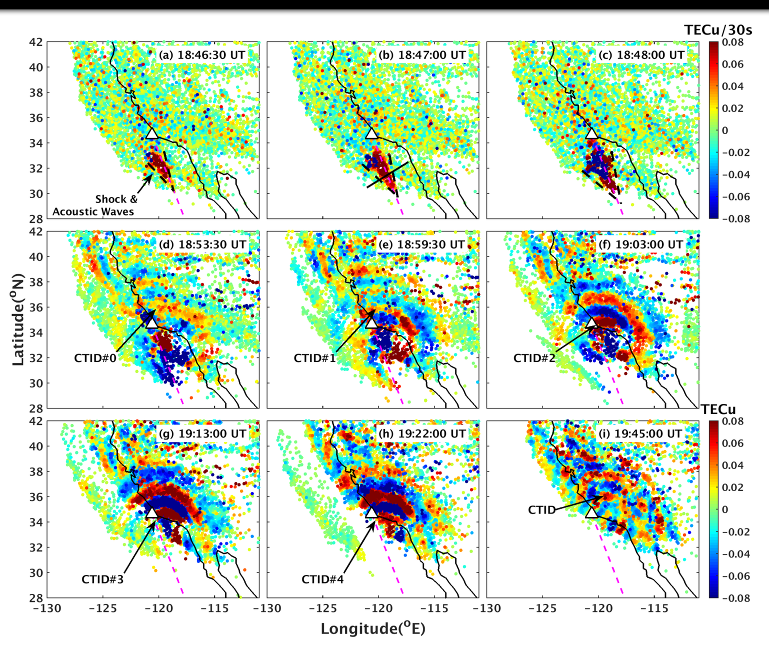
On 17 January 2016, a SpaceX Falcon 9 v1.1 rocket carrying an ocean altimetry satellite, JASON-3, launched from Vandenberg Air Force Base (California, US). We present first observation of rocket induced CGWs signatures in GPS TEC using the ground based GPS networks over North America. The distinct signatures of CTIDs with northward propagation appeared following the shock acoustic waves.

Travel Time Diagram of CTIDs

Filtered TEC display the propagation velocities of the shock waves , acoustic waves and CTIDs.

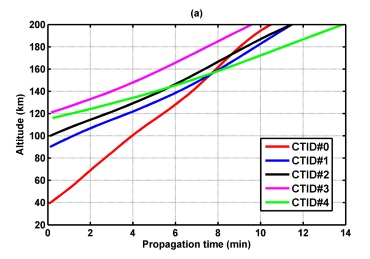


GPS TEC Observation

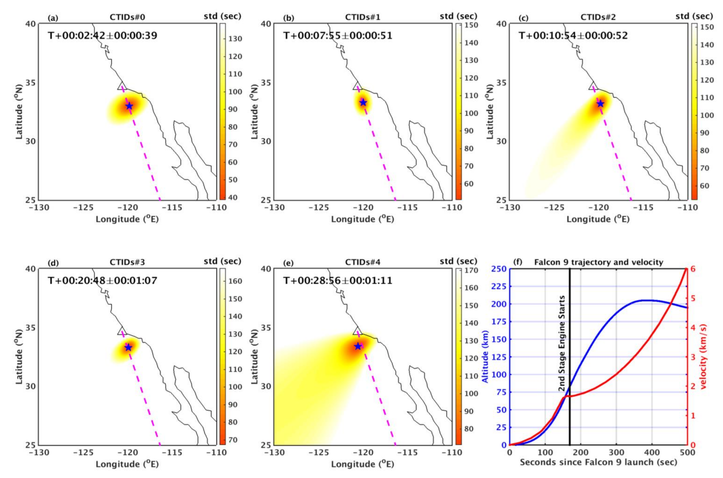


(a-c) The time rate change of TEC indicate the V-shaped signature of shock acoustic waves and (d-i) band pass filtering (8–15 min) of TEC indicate the very distinct concentric TIDs (CTIDs) triggered by the SpaceX Falcon 9 rocket.

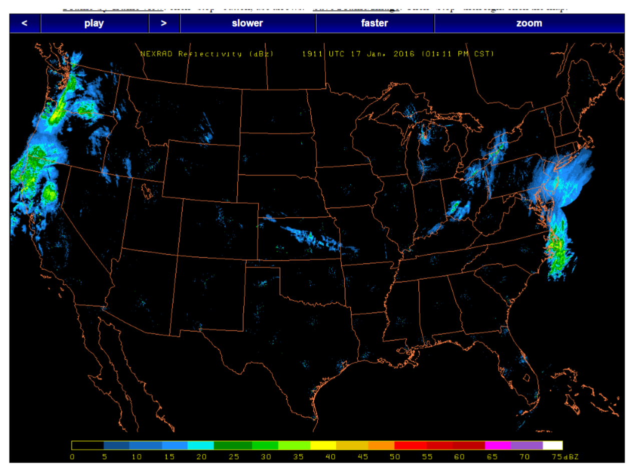
Search CTIDs Origin



The ray-tracing results suggest that the CTIDs are originated from the mesopause region.



NEXRAD Doppler Radar



Since the troposphere convection is the common source of CGWs. We have confirmed that there was no clear convection activities from NEXRAD radar reflectivity suggest that the rocket is the most likely source.

Summary

- We present concurrent observations of ionospheric disturbances of V-shaped shock-acoustic wave and ripple like CGWs triggered by the launch of a SpaceX Falcon 9 rocket on 17 January 2016.
- The ionospheric disturbances of shock acoustic wave are captured by the high pass filtering of GPS-TEC observations, followed by the disturbances of concentric gravity wave with the 8–15 minutes band pass filtering of TEC observations.
- The rocket-induced CTIDs last for an hour with the GW characteristics of ~200–400 km in horizontal wavelength, ~10.5–12.7 minutes in period and ~241–617 m/s horizontal phase velocities.
- The optimal source searching and reversed ray-tracing demonstrate that the CGWs are most likely generated by multiple CGWs after the ignition of 1st and 2nd stage rockets around and above the mesosphere region.