Observation and simulation of upper atmosphere perturbations due to rocket trajectories

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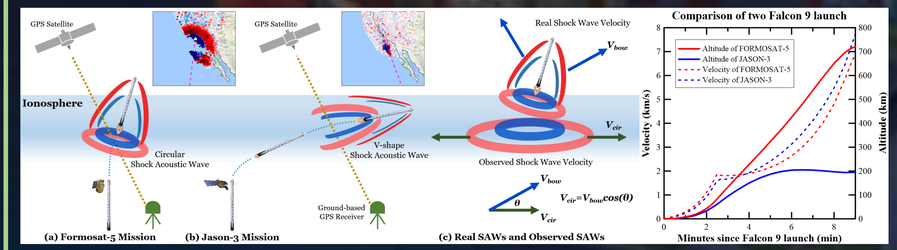
Abstract

We report the first observation of concentric traveling ionospheric disturbances triggered by the launch of a SpaceX Falcon 9 rocket carrying JASON-3 satellite in 2016. The rocket-triggered ionospheric disturbances show V-shape shock acoustic wave signature, followed by series of CTIDs. Another Falcon 9 rocket carrying Taiwan's FORMOSAT-5 Earth observation satellite into orbit in 2017. The lightly weighted solo payload enables the rocket to fly a unique lofted trajectory for a direct orbit insertion, thus generating gigantic circular shock acoustic waves (SAWs) in the ionosphere, following by an ionospheric hole due to rapid chemical reactions of rocket exhaust plumes and ionospheric plasma. Simulation of upper atmosphere perturbations due to rocket trajectories is investigated. We conclude the circular and V-shape ionospheric disturbances are triggered respectively by different orbit insertions of FORMOSAT-5 and JASON-3 based on a cosine angle relationship of actual SAWs and observed horizontal SAWs velocities. Understanding how the rocket launches affect our upper atmosphere and space environment is important as these anthropogenic space weather events are expected to increase at an enormous rate in the near future.

Motivation

Over the past few decades, since the 1960s, rapid developments in space technology have enabled human exploration beyond the Earth's orbit. With a large number of space vehicles carrying payloads into orbits, space weather effects linked to human activity have become an important issue.

- Rocket exhaust plumes generated ionospheric electron density depletions via chemical recombination process along the ascending trajectories.
- Kakinami et al. (2013) observed the V-shape SAWs in GPS-TEC triggered by a missile launch from North Korea on 12 December 2012 where the V-shape waves' horizontal phase velocities were much faster than records.
- Ding et al. (2014) observed the long-distance propagation of V-shape SAWs on both sides of the rocket trajectory during the launch of the Shenzhou 10 spacecraft in China on 11 June 2013.
- Lin, Shen, et al. (2017) first reported the concentric traveling ionospheric disturbances in GPS-TEC associated with the concentric gravity waves induced by the Falcon 9 rocket. The CGWs originated from the mesopause region and propagated into the ionosphere.



JASON-3

- 1st observation: Concentric traveling ionospheric disturbances triggered by rocket .
- Vehicle: SpaceX Falcon 9 rocket.
- Date: 17 January 2016.
- Disturbances:
  - SAWs rTEC
  - CTIDs 8–15 min
- CTIDs characteristics:
  - ✓ Source on the rocket trajectory.
  - ✓ Distances more than 1000 km.
  - ✓ Northward phase velocity 241–617 m/s.
  - ✓ Periods of 10.5–12.7 min.
  - ✓ Wavelength ~200–400 km.
  - ✓ Identified as Gravity waves!!
- Description of wave sources:

The HHT spectrum confirms clear rocket-related disturbances with enhanced amplitudes of TEC covering period of 3.3–13.9 min and being manifest for frequencies of 1.2–2.8 mHz (6–13.9 min time period) during the launch.

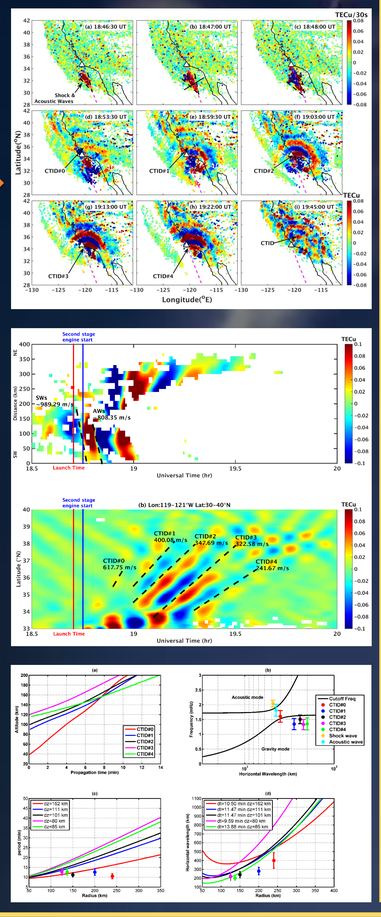
The optimal wave source searching and gravity wave ray-tracing technique suggested that the CTIDs have multiple sources which are originated from ~38–120 km altitude before and after the ignition of the 2nd stage rocket, ~200 s after liftoff.

a) Reversed ray tracing from 200 km to 38–120 km altitudes.

b) The theoretical cutoff frequency of acoustic and gravity modes.

c) CGWs periods and radius.

d) CGWs horizontal wavelength and radius.



FORMOSAT-5

- 1st observation: Gigantic circular shock acoustic wave in the ionosphere triggered by rocket with a steep initial ascent.
- Vehicle: SpaceX Falcon 9 rocket.
- Date: 24 August 2017.
- Disturbances:
  - Circular SAWs
  - Plasma hole ~3 hr

- Circular SAWs characteristics:
  - ✓ Rapidly appear in TEC ~5 min after the liftoff.
  - ✓ Extended ~1,500 km in diameter.
  - ✓ Emanated outward with ~20 min duration.
  - ✓ Horizontal phase velocities of ~629–726 m/s.
  - ✓ Periods of ~10.28 ± 1 min.
  - ✓ Horizontal wavelengths of ~390–450 km.
- Description of wave sources:

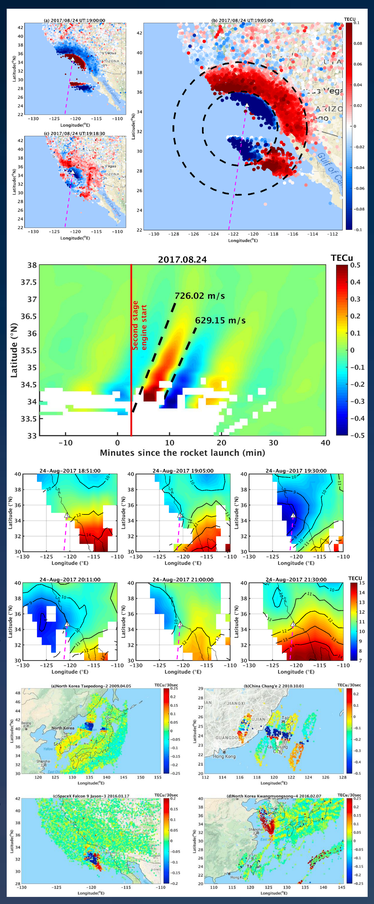
This is the largest rocket-induced circular SAWs on record, extending approximately 114–128°W in longitude and 26–39°N in latitude (~1,500 km in diameter), and was due to the unique, nearly vertical attitude of the rocket during orbit insertion.

- Plasma hole characteristics:
  - ✓ Created by the rocket-exhaust plume.
  - ✓ Large-scale ionospheric plasma hole (~900 km in diameter).
  - ✓ Subsequently created with 10–70% TEC depletions.
- Significance of such huge Plasma hole:

Unlike circular SAWs which have the smaller amplitude 3% of TEC fluctuations, the subsequent ionospheric plasma hole could cause spatial gradients in the ionospheric plasma potentially leading to a range error of ~1 m to the navigation and positioning.

Since L1 is a civilian-use signal, to be broadcast on the L1 frequency (1575.42 MHz),

$$\alpha_f = \frac{40.3 \cdot 10^{16}}{f^2} m_{signal\ delay}/TECu = 0.16\, m/TECu\,.$$



Model Simulation

The Whole Atmosphere Perturbation Model (WAPM) is a non-hydrostatic full fluid model solving both neutral atmosphere and ionosphere to identify the physics originally developed by Shinagawa and Oyama [2006] and Shinagawa et al. [2007], further extended to 3-D by Dr. Matsumura. The dynamics and chemistry are also modified particularly for the ionosphere. We input the perturbation term into the energy equation.

The momentum and heat are exchanged between neutral and ion, while the momentum energy loss by neutral-ion collision is converted to the internal energy gain by the neutral-ion frictional heating. Both the neutral atmosphere and the ionosphere calculations consider a nonlinear, non-hydrostatic compressible and single fluid model. The self-consistent ionospheric electrodynamic calculation and Ampere force to ion fluid are currently not considered, and the momentum equation is solved only in the field-aligned direction.

※ Background atmo NRLMSISE-00, composed of O, O_2, N_2, N, H, and He. (ratio fixed in time).

- ***Neutral Fluid Equations:***

$$\frac{\partial \rho}{\partial t} = -(u_n \cdot \nabla)\rho - \rho(\nabla \cdot u_n)$$

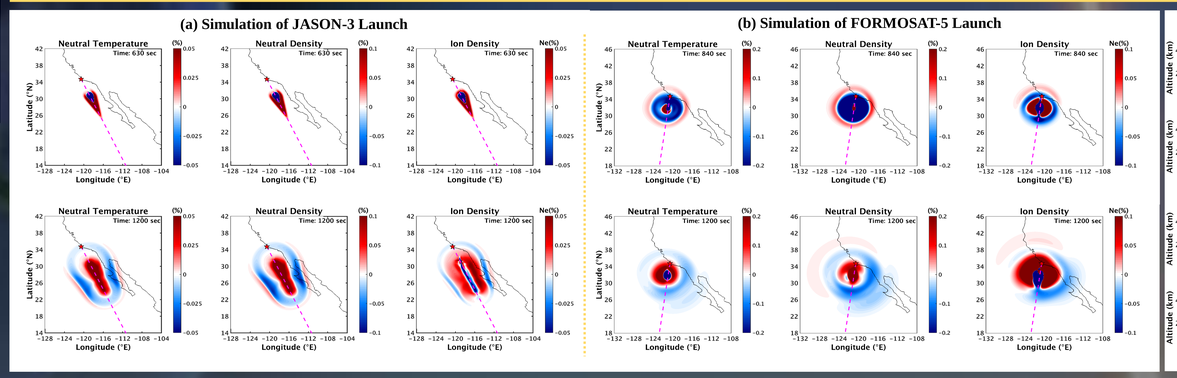
$$\frac{\partial u_n}{\partial t} = -(u_n \cdot \nabla)u_n - \frac{1}{\rho}\nabla P - g + \frac{1}{\rho}(\nabla \cdot \tau) - \nu_{ni}(u_n - V_i)$$

$$\frac{\partial T_n}{\partial t} = -(u_n \cdot \nabla)T_n - \frac{k_B T_n}{m_n c_v}(\nabla \cdot u_n) + \frac{1}{\rho c_v} \cdot (\kappa \nabla T_n) - \frac{3\nu_{ni} k_B}{m_n c_v}(T_n - T_i) + qr$$

$$P = \rho \frac{k_B}{m_n} T_n$$

where t denotes time, ρ is mass density, u_n is velocity vector of neutral, P is pressure, ν_{ni} is neutral-ion collision frequency, k_B is Boltzmann constant, T_n is neutral temperature, c_v is specific heat at constant volume, τ is viscosity stress tensor, κ is thermal conduction coefficient, and qr is the specific energy.

- Figure (a) and (b) show 100 km and 240km altitude horizontal profile of T_n, N_n, and N_e at 630 s, and 1200 s in two simulation cases, respectively.
- Figure (c) and (d) view from both parallel and perpendicular to the trajectories of the perturbation of N_n, and N_e at different timesteps, respectively.



Conclusions

- ➢ Concurrent observations of ionospheric disturbances of V-shaped SAWs and CGWs triggered by a Falcon 9 rocket in 2016. The disturbances of SAW propagated southward, while the disturbances of CGW propagated opposite way to more than 1000 km from 32°N to 40°N.
- ➢ Another launch event in 2017 shows the pronounced gigantic circular SAWs instantaneously appeared in the ionosphere ~5 min after liftoff. The circular shape instead of V-shape is most likely attributed to the steep ascent trajectory that acts as a point source to generate the circular SAWs.
- ➢ Simulation results agree with the hypothesis that the pattern of ionospheric disturbances, circular or V-shape, could be triggered by the different orbit insertions. Besides, the cosine angle relationship of actual SAWs and horizontal circular SAWs velocities is confirmed by the vertical disturbance profiles along the specific longitude and latitude.
- ➢ The process of CGWs occurrences at the JASON-3 case will be discussed by further model simulations.

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