

**Rare multiple ionospheric disturbances observed during the Artemis-II Lunar flyby voyage**

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**Key points**

The Artemis-II mission produced three different ionospheric disturbances, first by the rocket and later by Orion's orbit maneuver engines.

The powerful NASA rocket yielded weakest perturbations with shock-acoustic waves near launch site and gravity waves propagating outwards.

The less powerful Orion burns generated most intense perturbations extending across USA with direct energy deposition at ionosphere heights.

## Abstract

The total electron content observations during the Artemis-II Lunar mission revealed rare ionospheric perturbations occurring at three different occasions. The launch at 2235 UT on 1 April 2026 from Kennedy Space Center induced shock-acoustic and gravity wave modulations. Subsequent Apogee Raise Maneuver (ARM) performed at 0023 UT on 2 April triggered shock waves and much intense large-scale disturbances that elongated  $\sim 50^\circ$  longitude across North America. The third orbital maneuver conducted as part of trans-Lunar injection (TLI) at 2349 UT on 2 April, yielded similar, but weaker large-scale perturbations. This is the first time a single space mission producing such multiple ionospheric disturbances over the same region. The observed amplitudes suggest that despite releasing large exhaust energy, the disturbances during the rocket ascent produced weaker perturbations, whereas fewer amounts of direct energy deposition at ionosphere altitudes during ARM and TLI yielded up to 9 times intense perturbations elongated along the trajectory.

**Key words.** Artemis-II, anthropogenic space weather, rocket-induced ionospheric disturbances, total electron content (TEC), traveling ionospheric disturbances (TIDs), rocket exhaust, orbital maneuver burns

## Plain Language Summary

Though space launches often induce ionosphere disturbances, the Artemis-II Lunar mission for the first time produced extremely rare occurrences of perturbations over the same geographic region on three different occasions, (i) during the lift-off, (ii) about 2-hours later, and (iii) and more than 24-hours after lift-off. Detailed analysis using ground-based total electron content (TEC) measurements over USA shows that the first disturbances exhibit wave characteristics that are usually reported during rocket launches associated with atmospheric perturbations from the engine burn. However, the second and third disturbances exhibited very different morphology, appearing as unusually elongated wave structures that cover the entire North American longitudes. Comparisons with estimated mission trajectory and available launch updates suggest that the second and third unusual perturbations were related to specific orbit maneuvers performed as part of elevating the Apogee of Orion and subsequent injection into the Lunar gravitational field. Unlike the launch, the engine burns required to achieve these orbit changes released their energy directly within the ionosphere, perturbing the plasma far more strongly despite the energy being smaller.

## 1. Introduction

The ionosphere is often disturbed during rocket, or missile launches, causing anthropogenic or human-made space weather (Mendillo et al., 2008). Such disturbances gained attention following the early reports of F-region electron density decrease during a missile transit (Booker, 1961),

shock cones and acoustic disturbances after Apollo missions (Arendt 1971; Cotten & Donn, 1971; Tolstoy, 1970), and large-scale ionosphere hole by the Skylab launch (Mendillo et al., 1975). The perturbations generally fall into three categories: shock fronts, electron density undulations, and bite-outs. Comprehensive simulations by Lin et al. (2017a) show that the energy burst from the rocket ignition at supersonic speeds generates V-shaped shock-fronts propagating outward from the trajectory (Choi et al., 2025; Ding et al., 2014; Kakinami et al., 2013; Lin et al., 2014; Wang et al., 2023), and the rapid exhaust plume discharge triggers shock-acoustic or gravity modulations (Afraimovich et al., 2001; Calais & Minster, 1996; Chou et al., 2018a; Lin et al., 2017b; Mabie et al., 2016; Noble, 1990; Rajesh et al., 2025). Similarly, ion outflow from the impulsive pressure bulge and chemical loss by rocket-exhaust materials generates electron density dropouts and ionosphere holes (Choi et al., 2025; Chou et al., 2018a; 2018b; Furuya & Heki, 2008; Li et al., 2022; Liu et al., 2018; Mendillo et al., 1975; Park et al., 2016, 2022; Wang et al., 2023; Rajesh et al., 2025).

Several factors like the launch vehicle used, nature of propellants, trajectory inclination, launch sequence, local-time, and location, could influence the observed space weather impacts (Bowden et al., 2020; Chou et al., 2018b; Ducourtieux, 2022; Lin et al., 2014; 2017a; 2017b; Ozeki & Heki, 2010; Rajesh et al., 2025). The ensuing perturbations generally occur near the launch-site and last several minutes to a few hours. Except for a rare event of launches over similar locations and time on successive days (Rajesh et al., 2025), to date, no single mission has yielded ionospheric variations on multiple occasions. However, the Artemis-II launch produced repeated ionospheric perturbations in total electron content (TEC) measurements. The TEC variations revealed weak but distinct shock acoustic and gravity wave modulations a few minutes after lift-off. Unlike previous space launches, a second instance of intense TEC perturbations appeared ~1-hour later, extending across wider longitudes. Similar perturbations then occurred for a third time after ~24-hours over the same location.

These second and third disturbances are caused by subsequent orbit maneuvers, making this the first mission producing three separate ionospheric variations from a single launch. This study examines the impacts of these rare multiple ionospheric disturbances caused by different ignition systems. Though the orbit maneuvers also generated ionospheric depletions, they will be examined in a separate study.

## **2. Data and Methods**

This study utilizes 30-sec sampled Global Navigation Satellite System (GNSS) observations from GPS (Global Positioning System), GLONASS (Global Navigation Satellite System), and Galileo constellations from ~3,500 ground stations over America to derive vertical TECs (Liu et al., 1996) using ionosphere pierce point (IPP) altitude of 300 km and 20° elevation cut-off. The ionospheric perturbations during the Artemis-II launch are extracted by using fifth-order Butterworth bandpass filtered TECs (2-10 and 8-15 mins) and high-pass filtered differential TECs

(dTECs) by removing a 31-point large-scale background. Distance-time maps (keograms) of the filtered TECs are constructed and the horizontal phase velocity, period, and wavelength of the modulations are derived. The keograms are obtained by calculating the distances from a given reference point to individual IPP locations within a selected rectangular region normal to the wavefronts. The rectangular region and the reference location are marked on the illustrations for each disturbance examined.

Since the JPL-Horizons ephemeris provides the Artemis-II state vectors only from 3-hours 22-min after launch, the trajectory from launch to Perigee was reconstructed using two-body Keplerian model (e.g., Vallado, 2013) with available orbital parameters such as launch inclination, initial orbital velocity, Apogee and Perigee altitudes. The gap from this estimated Perigee point to the JPL-Horizons state vectors is then bridged by spherical linear interpolation of the position vector, with the radial distance following the Keplerian profile and velocity continuity preserved by piecewise cubic Hermite interpolating polynomial. This spatiotemporal reconstruction is essential for correlating the spacecraft's kinematic parameters with localized ionospheric perturbations.

### **3. Artemis-II induced Ionospheric Perturbations**

Second in the series of missions planned by National Aeronautics and Space Administration (NASA), the Artemis-II Lunar flyby lifted off from Kennedy Space Center, at about 2235 UT on 1 April 2026. The launch powered by NASA's heavy-lift Space-Launch-System (SLS) rocket deployed Orion spacecraft and Interim-Cryogenic-Propulsion-Stage (ICPS) unit to an initial orbit ~8-min after lift-off. About 49-min after launch, a Perigee Raise Maneuver (PRM) inserted Orion and the ICPS into a low-Earth orbit with 185 km perigee. Later, an Apogee Raise Maneuver (ARM) performed by ICPS about 108-min post-launch for about 18-min, placed Orion in a high-Earth orbit and subsequently detached from ICPS. After 25-hours and 14-min post-launch, a Trans-Lunar Injection (TLI) burn for 5-min and 50-second was conducted by Orion's Orbital-Maneuvering-System-Engine (OMSE) at 2349 UT on 2 April, propelling Orion into Moon's gravitational influence.

This launch sequence produced ionospheric disturbances at three distinct phases, following lift-off and during ARM and TLI burns. Figure 1 illustrates the first group of TIDs in bandpass filtered TECs and corresponding keograms following the SLS launch over three geographical sectors: in the immediate launch vicinity (R1), and regions extending to the south (R2) and north (R3) of the launch site. The figure displays selected maps of prominent TIDs over these regions and movies S1 and S2 (Supporting Information, SI) include their complete time sequences. These disturbances emerge over R1 within ~10 min of lift-off and propagate at ~1.3 km/s horizontal phase velocity, having 4-5 min period and ~350 km wavelength (Figure 1a), suggesting shock-acoustic characteristics. Over R2 and R3, farther from launch site, northward and southward propagating disturbances with horizontal phase velocities of 600-670 m/s, periods of 12.5–13.5

mins and wavelength of  $\sim 400$  km appear  $\sim 20$ -min after launch (Figures 1b, 1c), apparently revealing gravity wave signatures. The predominantly southward propagation over R1 lasts  $\sim 25$  min and is limited to a range of  $\sim 500$  km (Figure 1a). In comparison, R2 and R3 disturbances traverse distances  $> 1000$  km (Figures 1b, 1c), with pronounced amplitudes to the south (equatorward) of the launch site and apparent damping to the north (poleward). The maximum amplitude of these perturbations is  $\sim 0.16$  TECU.

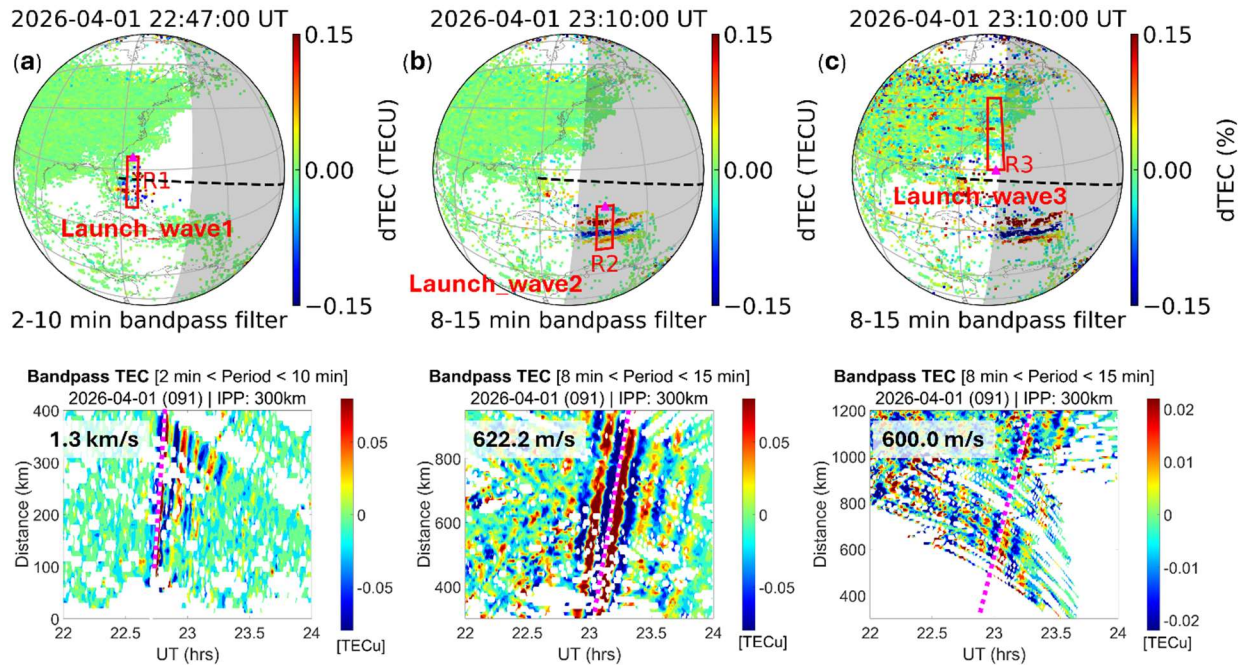


**Figure 1.** Illustration of launch-stage TIDs (named as Launch\_wave1, 2, and 3) following the lift-off. (top) Selected TID's on 1 April (a) at 2247 UT in 2-10 min bandpass TECs and (b-c) at 2310 UT in 8-15 min bandpass TECs. (bottom) The corresponding distance-time keograms by using the observations in the regions R1, R2 and R3 drawn on top panels, where the magenta triangle denotes the reference point for distance. The estimated horizontal propagation velocities are marked on the bottom panels.

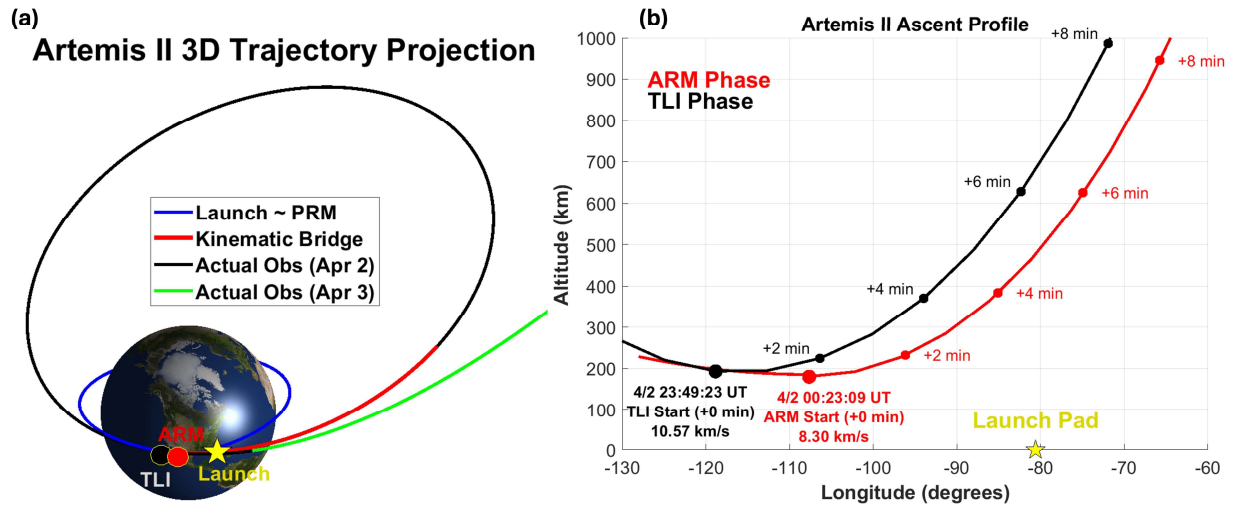


**Figure 2.** Estimated and officially available mission trajectory. (a) The illustration of the estimated trajectory after launch based on available launch parameters and orbital details until the Perigee (blue line), the interpolated trajectory segment as a kinematic bridge from the Perigee to the JPL-Horizons trajectory (red line), the available trajectories (denoted as ‘Actual Obs’) for April 2 (black line) and April 3 (green line). The launch location (yellow asterisk), ARM and TLI burn locations (red and black circles) are marked on the globe. (b) The altitude and longitude locations during ARM (red) and TLI (black) burns. The ARM and TLI burn times and corresponding spacecraft velocity are marked on the figure, with filled circles denoting the subsequent locations every 2-min.

Before analyzing ARM and TLI TIDs, it is necessary to examine Orion trajectory after launch. Figure 2a illustrates the polar projection of the synthesized trajectory, marking the launch site, and ARM, TLI burns. Figure 2b tracks the corresponding altitude and longitude variations over time. From the figure, the ARM burn started when the spacecraft was over 28.5°N and 107.7°W. Similarly, the TLI burn was initiated over 27.4°N and 118.9°W. During the burn period, the spacecraft orbit remained within ionospheric altitudes of 190-400 km over 120°-60°W, at ~28°N (Figure 2b).

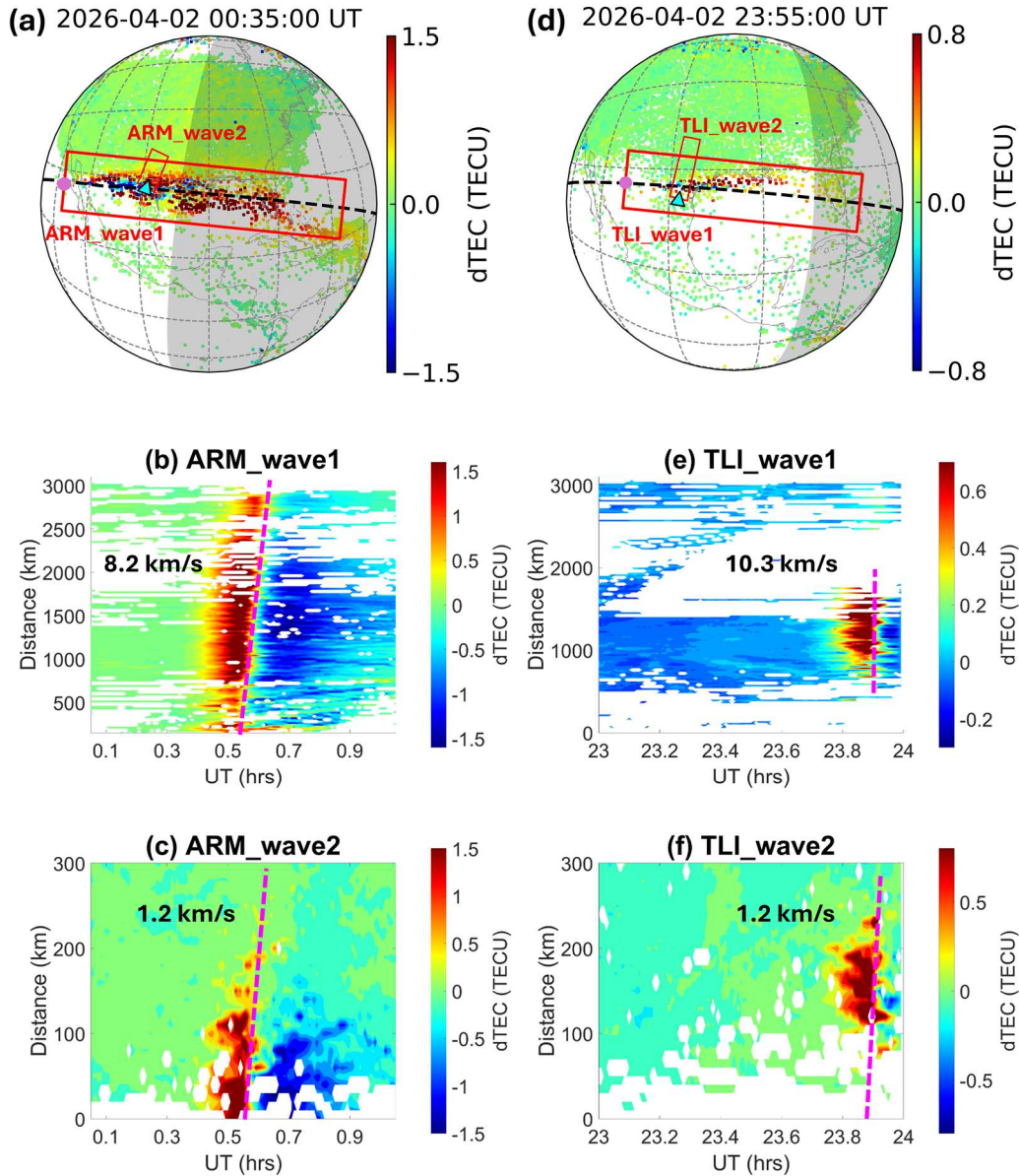


**Figure 3.** The longitudinally elongated ionospheric disturbances and bow waves during ARM and TLI stages. (Left) (a) dTEC maps showing large-scale disturbances (the rectangle ARM\_wave1) aligned with the Artemis-II trajectory (dashed line) and bow wave fronts generated by the supersonic motion (rectangle ARM\_wave2). (b) dTEC keograms along ARM\_wave1 with the magenta circle as reference point. (c) dTEC keograms for ARM\_wave2 with cyan triangle marking the reference. The corresponding estimated propagation velocities are noted on panels (b) and (c). (Right) (d-f) Same as the left panels, but during TLI stage showing similar elongated disturbances (TLI\_wave1) and bow wave front (TLI\_wave2).

Figure 3 displays the second and third groups of TIDs triggered during the ARM and TLI burns. In stark contrast to the launch phase TIDs (Figure 1), the figure captures rare and

significantly intense ionospheric disturbances. The dTEC maps (Figures 3a, 3d) reveal perturbations traversing West-East across United States (see movies S3-S4, SI). The ARM\_wave1 disturbances in Figure 3a originate near the ARM ignition coordinates (see Figure 2) and remain predominantly confined to the horizontal trajectory, exhibiting highly restricted latitudinal propagation. The disturbances span the longitudes of 110°W to 60°W, encompassing distances >5000 km. This is the first report of such elongated disturbances generated during a spacecraft launch. The maximum amplitude of the disturbances is 2.5-3.7 TECU, much larger compared to earlier launches (Chou et al., 2018b).

Figures 3 b-c examine the propagation of the disturbances along the trajectory (ARM\_wave1) and the waves at the sheath moving away from the trajectory (ARM\_wave2). The ARM\_wave1 disturbances propagate at a horizontal velocity of 8.2 km/s (Figure 3b), nearly identical to the orbital velocity of Orion (~8.3 km/s) during the maneuver (Figure 2). The alignment of the ARM\_wave1 disturbances appears to deviate from the estimated trajectory beyond 80°W, shifting southward (equatorward). Apparently, the ARM burn caused large vertical acceleration over this region (Figure 2), and in the absence of official trajectory data it is unclear whether the actual flight path had deviated. The ARM\_wave2 show very restricted outward propagation within 200 km at 1.2 km/s (Figure 3c), corresponding to shock-acoustic speed in ionosphere.

While displaying a similar spatial morphology as ARM\_wave1, the TLI\_wave1 perturbations (Figure 3d) span only about half (~20°) the longitude region, appearing over 100°W to 80°W. The overall amplitude of the dTEC structures is within 1.0–2.4 TECU. The estimated propagation velocity of 10.3 km/s for TLI\_wave1 (Figure 3e) matches the Orion velocity of ~10.5 km/s during this period. The localized fronts at the sheath of the bow (Figure 3f) propagate at velocities identical to ARM\_wave2 disturbances.

Figure 4 compares the propagation characteristics of these rare multiple disturbances with the theoretical dispersion relationship (Hines, 1960), following the approach described by Lin et al. (2017b). From Figure 4, the Launch\_wave1 TIDs in region R1 (Figure 1a) fall in the acoustic regime, whereas Launch\_wave2 and Launch\_wave3 (Figures 1b, 1c) align with gravity mode dispersion curves. The figure also includes ARM\_wave2 (Figure 3a) and TLI\_wave2 (Figure 3d) perturbations to examine their dispersion characteristics. Since their periods and wavelengths could not be estimated from the dTEC results, corresponding 2-10 min bandpass filtered results are instead used. Though bandpass filtering introduces artificial phase shifts, this does not hinder reasonably estimating such wave characteristics. The results confirm the acoustic nature of ARM\_wave2 and TLI\_wave2 disturbances. As ARM\_wave1 and TLI\_wave1 disturbances did not exhibit periodic patterns, they are excluded in Figure 4.

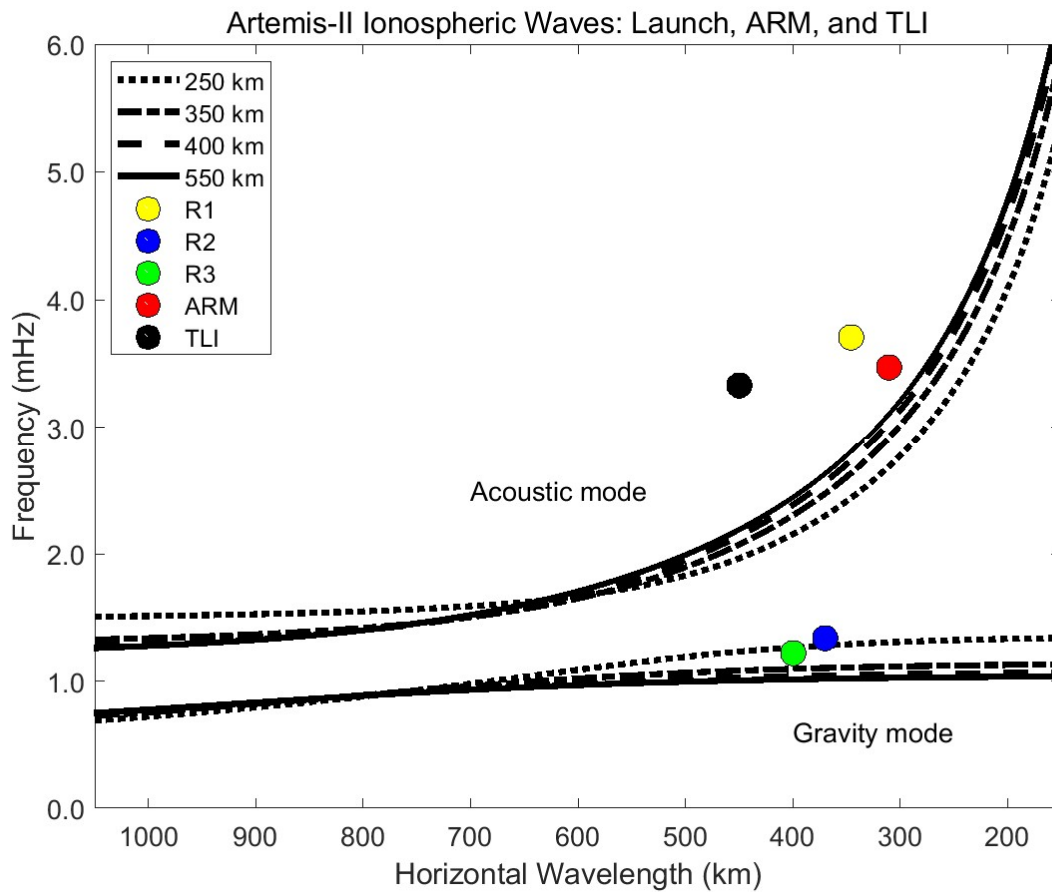
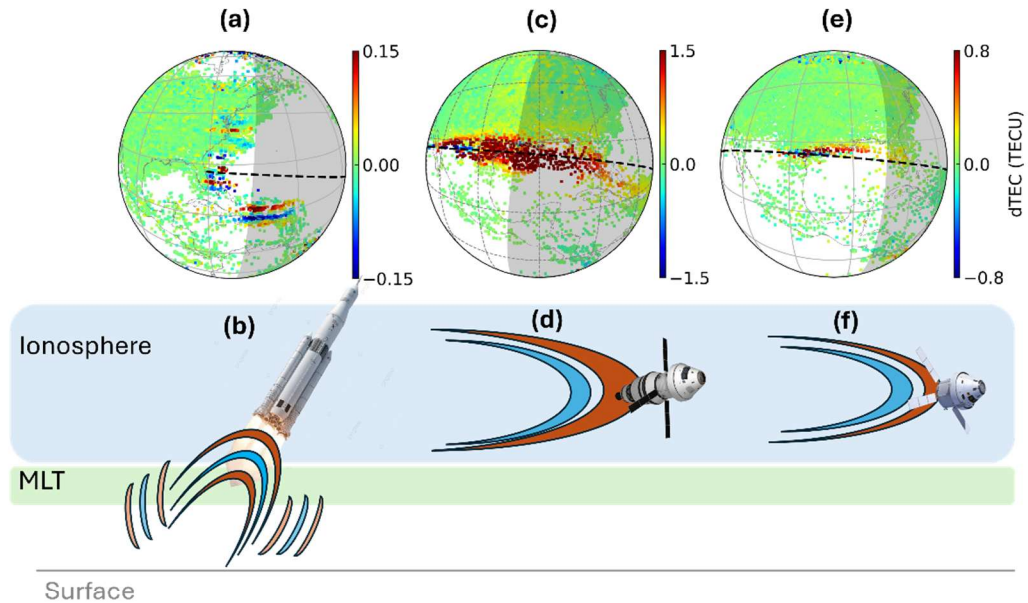


**Figure 4.** The dispersion characteristics of the observed TIDs. The different lines show theoretical dispersion curves for acoustic and gravity wave modes at 250, 350, 400 and 550 km altitudes. The colored symbols denote the intrinsic frequencies and horizontal wavelengths of the observed launch-stage TIDs over the regions R1 (yellow), R2 (blue), and R3 (green). The red and black symbols correspond to the bandpass filtered ARM\_wave2 and TLI\_wave2 perturbations.

#### 4. Discussion and Conclusion

The above results for the first time show three different instances of ionospheric disturbances triggered by a single space mission over the same geographical region within a time span of about 25-hours. This provides a unique opportunity to examine the impact of anthropogenic energy deposition at different atmospheric layers, as SLS flew from ground to ionosphere whereas ARM and TLI burns deposited energy entirely at ionosphere heights. Figure 5 summarizes the three different perturbations triggered during the Artemis-II voyage. The launch by the powerful SLS rocket with a core-stage thrust of 8,896 kN, delivered  $\sim 7.9 \times 10^{12}$  J (Joules) energy burning for 8 min as it cruised to initial orbit. This triggered acoustic and gravity waves in the atmosphere as

sketched in Figure 5b, propagating upward and imparting the modulations in TEC observations (Figure 5a), as often reported in literature (Choi et al., 2025, and references therein).



| Parameter               |              | SLS Launch           | ICPS ARM             | Orion TLI            |
|-------------------------|--------------|----------------------|----------------------|----------------------|
| Maximum thrust (kN)     |              | 8896                 | 110.1                | 26.7                 |
| Total Energy (J)        |              | $7.9 \times 10^{12}$ | $2.7 \times 10^{11}$ | $1.5 \times 10^{10}$ |
| Orbital velocity (km/s) |              | N/A                  | ~8.3                 | ~10.5                |
| TEC perturbation [TECU] | Differential | N/A                  | 2.5~3.7              | 1.0~2.4              |
|                         | Bandpass     | 0.16                 | 0.7~1.4              | 0.4~1.2              |

**Figure 5.** Schematic summary of the three perturbation stages of Artemis-II mission. (left) SLS launch, (middle) ICPS ARM, and (right) Orion TLI burn. For each stage, the panels show (top) the observed TEC perturbations and (center) the schematic mechanism of the corresponding disturbances from the exhaust of each vehicle. The bottom table lists the engine specifications from mission documents and the largest amplitude of the perturbations in differential (dTEC) and bandpass filtered TECs.

In contrast to the ascending SLS rocket, the ARM and TLI burns involved relatively smaller energy deposition. The 18-min long ICPS ignition provided a thrust of 110.0 kN, releasing  $\sim 2.7 \times 10^{11}$  J energy. The OMSE with a thrust of 26.7 kN was ignited for 5-min and 50-seconds during TLI, releasing  $\sim 1.5 \times 10^{10}$  J. Despite depositing 1-2 orders of magnitude lesser energy than the SLS launch, the ARM and TLI phases yielded much intense perturbations extending over a wider geographic region along the spacecraft trajectory (Figures 3, 5c-5e). Based on dTECs, the

observed maximum amplitudes are respectively 15~23 and 6~15 times greater than that during the SLS launch (Figure 5). Since dTECs could not be applied to the SLS launch disturbances, a more reasonable comparison to avoid overestimating the differences would be to use the bandpass filtered amplitudes during ARM and TLI stages. This still yields about 4~9 and 2~8 times greater amplitudes (Figure 5). Thus, direct energy release within the ionosphere induces much intense variations than those produced by coupling from lower altitudes. The larger energy release and longer burn duration results in more intense perturbations during the ARM compared to TLI (Figure 3).

This concentrated energy input with extended burn within the ionosphere altitudes generates localized pressure bulge and shock fronts (Figures 5d-5f), consistent with the excitation mechanism by Lin et al. (2017a), apparently forcing large-scale disturbances to propagate horizontally, aligning along the trajectory over distances of >5000 km. The close agreement of the horizontal propagation with the spacecraft velocity indicates that these trajectory-aligned disturbances are the forced responses continuously driven by the hypersonic heat source of the engine exhaust, with their spatial structure governed by the orbital velocity. Note that the ARM and TLI burns did not trigger any gravity wave disturbances as these ignitions occurred within the highly viscous thermosphere, where such perturbations might be damped by the large kinematic viscosity and thermal diffusivity (Vadas & Fritts, 2005). The kinematic viscosity ( $\nu$ ) at 90 km is about  $6.5 \text{ m}^2 \text{ s}^{-1}$  (Vadas & Fritts, 2005), whereas over the altitudes of 200 km the value becomes  $10^4 \sim 10^5 \text{ m}^2 \text{ s}^{-1}$  (Vadas & Nicolls, 2012). With such large  $\nu$ , gravity waves may not be generated or sustained at the ARM and TLI burn altitudes.

There are several rare and unique aspects for these Artemis-II events compared to other launches. First, a single mission produced three separate groups of disturbances over the same region, whereas earlier launches yielded just once. Second, the ARM and TLI disturbances formed longitudinally elongated structures extending >5,000 km along the trajectory, unlike the V-shaped or circular wavefronts formed near launch-site reported previously (Chou et al., 2018b; Lin et al., 2014). Third, these disturbances propagated at spacecraft orbital speeds of 8-10 km/s, nearly an order of magnitude faster than the launch-induced shock-acoustic speeds reported so far (Afraimovich et al., 2001; Chou et al., 2018b; Lin et al., 2014). Fourth, the disturbances are driven by sustained maneuver burns performed within F-region altitudes, in contrast to the exhaust release of ascending rockets in previous studies.

These multiple ionospheric disturbances associated with Artemis-II provided rare opportunity to understand anthropogenic impacts on space environment. The SLS deposited intense energy during launch but triggered comparatively weaker shock-acoustic perturbations near the launch-site and gravity wave disturbances propagating outward from trajectory. Though the ARM and TLI burns involved lesser energy release, the direct deposition at ionospheric altitudes yielded up to 9 times intense perturbations elongated along the trajectory, but with limited propagation at the sheath of the bow. Thus, ionospheric perturbations induced by space launches not only depend on the amount of energy deposited, the altitude of energy release is also important. With very large

orbital velocity and extended burn duration, the pressure bulge by localized ignition produces large-scale trajectory-aligned disturbances to propagate horizontally. These findings establish the orbital maneuver burns performed within the ionosphere as a distinct and repeatable source of anthropogenic space weather. Previous rocket launches yielded perturbations of 0.5-0.75 TECU, propagating at 600-1,500 m/s, lasting for 15-20 min (c.f., Chou et al., 2018b and Li et al., 2025). In comparison, the ARM and TLI disturbances had amplitudes ranging 2.5-3.7 TECU, propagating at speeds of 8-10 km/s for over 1-hr duration. Thus, continuous monitoring with dense GNSS networks and dedicated modeling of in-situ exhaust energy deposition will be essential to assess such recurring impacts on ionosphere, GNSS-based applications, and high-frequency communications.

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## Open Research

The GNSS data used in this study are obtained from the publicly available networks of International GNSS Service (<http://garner.ucsd.edu/pub/rinex>), Continuously Operating Reference Stations of National Oceanic and Atmospheric Administration (<https://geodesy.noaa.gov/corsdata/rinex>), Pacific Northwest Geodetic Array of Central Washington University (<https://www.geodesy.org/pub/data>), the Northern California Earthquake Data Center (NCEDC) of University of California Berkeley Seismological Laboratory (<https://ncedc.org/gps/rinex>), and Brazilian Institute of Geophysics and Statistics ([https://geoftp.ibge.gov.br/informacoes\\_sobre\\_posicionamento\\_geodesico/rbmc/dados](https://geoftp.ibge.gov.br/informacoes_sobre_posicionamento_geodesico/rbmc/dados)). The rocket and spacecraft details and launch sequence of Artemis-II are obtained from the NASA missions website and official *press kit* (<https://www.nasa.gov/mission/artemis-ii/>, <https://www.nasa.gov/artemis-ii-press-kit/>). The publicly available Artemis-II trajectory information is retrieved from Jet Propulsion Laboratory (JPL) Horizons interface (<https://ssd.jpl.nasa.gov/horizons/app.html#/>).

322    **Conflict of Interest Disclosure**

323    “The authors declare there are no conflicts of interest for this manuscript.”

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