

# Three-Dimensional Hollow Tubular Structure of Rocket Chemical Depletion

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## Key Points:

(1) The vertical structure of rocket-exhausted ionospheric electron density depletion was captured by COSMIC-1 radio occultation data.

(2) Reconstructs the three-dimensional tubular electron density hole from rocket exhaust based on multi-source observations and simulation.

(3) The evolution of REDs should be mainly divided into three stages: "rapid formation, diffusion-driven growth, and diffusion-driven recovery."

## Abstract

The rocket launch process causes a series of disturbances in the ionosphere, among which a typical phenomenon is the formation of ionospheric electron density depletions caused by chemical reactions involving rocket exhaust, known as Holes in the Ionosphere from Rocket Exhaust (HIREs). Current research on the HIREs mainly focuses on the horizontal features observed from ground-based GNSS data. By utilizing COSMIC radio occultation data, we clearly observed the vertical structure of HIREs following the launch of an ATLAS-V rocket from Cape Canaveral Air Force Station on May 22, 2014. Additionally, combining ground-based GNSS, Swarm satellite observations, and numerical simulations, we delineated, for the first time, the three-dimensional "hollow tube" structure of the HIREs. Then, the spatiotemporal evolution of the HIREs is analyzed, and considered to mainly consist of three stages: "rapid formation, diffusion-driven growth, and diffusion-driven recovery". The study contributes to a deeper understanding of the formation and development of artificial ionospheric plasma hollow-tubes.

## Plain Language Summary

A rocket launch released gases high into the atmosphere and caused a large region where the number of free electrons dropped sharply. We combined satellite measurements, ground observations, and simulations to reveal the three-dimensional shape and evolution of this electron loss for the first time. The depletion formed quickly, expanded as the gases spread, and then

38 slowly recovered. These results help us understand how frequent launches briefly disturb the space  
39 environment above Earth.

## 40 **1 Introduction**

41 During rocket launches, the ionosphere undergoes a range of physical and chemical interactions,  
42 resulting in various disturbances. Rockets traveling at supersonic speeds through the mesosphere,  
43 alongside the explosive release of exhaust gases, generate shock waves and Atmospheric  
44 Acoustic-Gravity Waves (AGWs) (e.g., Arendt, 1971; Noble, 1990; Jacobson & Carlos, 1994; Li et  
45 al., 1994). These disturbances induce traveling ionospheric disturbances (TIDs), which are  
46 frequently observed within a certain range along the rocket's trajectory and have been extensively  
47 documented (e.g., Kakinami et al., 2013; Lin et al., 2017; Chou et al., 2018; Yasyukevich et al.,  
48 2024). The rocket's propulsion relies on rapidly ejecting large volumes of combustion products,  
49 part of which are released into the atmosphere and can impact climate and stratospheric ozone  
50 (Barker et al., 2024). As the rocket ascends into the ionosphere, these exhaust gases expand  
51 rapidly in the ionosphere, they act like a "snowplow", pushing background plasma outward and  
52 forming a density pile-up layer (e.g., Booker, 1961; Mendillo et al., 1988). Simultaneously, the  
53 exhaust pressure drops sharply to match the background ionosphere, transitioning into a free  
54 diffusion process. This exhaust, rich in H<sub>2</sub>O, H<sub>2</sub>, and CO<sub>2</sub>, undergoes a series of chemical  
55 reactions during diffusion, further depleting ionospheric electrons and forming ionospheric  
56 electron density "holes" known as rocket-exhausted depletions (REDs) (e.g., Mendillo et al., 1975,  
57 2008; Bernhardt et al., 2001). These chemical reactions produce excited oxygen atoms (O(<sup>1</sup>D))  
58 and hydroxyl radicals (OH), which emit 630 nm red light and 135.6 nm ultraviolet emissions,  
59 observable by airglow imagers, sounding rockets, and satellite instruments (e.g., Mendillo et al.,  
60 2008; Liu et al., 2006; Park et al., 2022).

61 REDs were first detected by sounding instruments (Booker, 1961) and through Faraday rotation of  
62 satellite signals (Mendillo et al., 1975; Wand and Mendillo, 1984). Subsequent studies primarily  
63 relied on GNSS-TEC data to capture the 2D horizontal distribution of REDs (e.g., Mendillo et al.,  
64 2008; Furuya and Heki, 2008; Nakashima and Heki, 2014). Furthermore, Park et al. (2015, 2016,  
65 2022) observed associated electron density depletions using in-situ satellite measurements even  
66 six hours after the rocket launch, and captured 2D depletion distributions using satellite ultraviolet  
67 spectrometers. Numerous observations indicate that REDs typically emerge around 5-7 minutes  
68 after launch, persisting for 0.5 to 6 hours (e.g., Bernhardt et al., 2001; Mendillo et al., 2008;  
69 Nakashima & Heki, 2014; Park et al., 2016). The depletion regions generally extend laterally  
70 along the rocket's trajectory, with widths of approximately 300-500 km and lengths exceeding  
71 2000 km (e.g., Liu et al., 2018; Ozeki & Heki, 2010; Mendillo et al., 2008; Zhao et al., 2024).  
72 Inside REDs, total electron content (TEC) drops by 3-22 TECU compared to the background  
73 ionosphere (e.g., Liu et al., 2018; Park et al., 2022; Zhao et al., 2024), while maximum electron  
74 density reductions range from 20% to 95% (e.g., Furuya & Heki, 2008; Park et al., 2016; Mendillo  
75 et al., 1984, 2008; Zhao et al., 2024).

76 Current REDs observations largely rely on GNSS-TEC data, with a few nighttime launches  
77 observable through optical imaging (e.g., Mendillo et al., 2008; Park et al., 2022), which mainly  
78 capture horizontal 2D structures. Vertical structure observations remain scarce. A limited number  
79 of studies using incoherent scatter radar (e.g., Wand & Mendillo, 1984; Bernhardt et al., 1998,

80 2012; Zhao et al., 2024) have captured vertical profiles of REDs. Zhao et al. (2024) reported  
81 observations of ionospheric REDs structure during two rocket launches, and the results showed  
82 that REDs can extend to ~200-700 km in altitude. The maximum depletion altitude for the  
83 afternoon event is 425 km, and the maximum depletion altitude for the midnight event is 283 km.  
84 Park et al. (2015, 2016) detected REDs diffusing to satellite orbit heights (450 km and 518 km)  
85 through Swarm satellite in-situ measurements. Park et al. (2022) also utilized the GOLD imager,  
86 Madrigal TEC, and multiple Low-Earth-Orbit satellites, with COSMIC-2 data suggesting an  
87 increase in ionospheric slab thickness at the depletion center, which may indirectly support the  
88 presence of vertical structural features. Meanwhile, the COSMIC-2 Gridded Ionospheric  
89 Specification (GIS) product offers some insight into the three-dimensional distribution of electron  
90 density depletions. However, given the relatively limited spatiotemporal resolution of the GIS data  
91 ( $5^{\circ} \times 2.5^{\circ}$  in latitude and longitude, with a temporal resolution of 1 hour), which is somewhat  
92 coarse compared to the typical width (~500 km) of REDs, it remains challenging to fully resolve  
93 the fine three-dimensional structure and evolutionary process of these features.  
94 In this study, we obtained clear observations of the vertical structure of REDs using COSMIC-1  
95 occultation data. Combining multi-source observations from COSMIC-1, Swarm satellites, and  
96 ground-based GNSS, we revealed the 3D hollow-tube structure of REDs and their evolutionary  
97 characteristics, offering a new perspective on rocket launch ionospheric disturbances. Additionally,  
98 high-resolution 3D simulations further validated the feasibility and reliability of the depletion  
99 modeling.

## 100 **2 Data and Simulation**

### 101 **2.1 Rocket Launch Event**

102 Event-1: On May 22, 2014, an Atlas-V Rocket was launched from Cape Canaveral Air Force  
103 Station by United Launch Alliance (ULA) at 13:09 UT. Event-2: On May 20, 2015, a similar  
104 Atlas-V was launched at the same station by ULA at 15:09 UT. REDs from two launch events  
105 were reported by Park et al. (2016) using satellite in-situ observations. This study primarily  
106 focuses on Event-1, while Event-2 serves as a supplementary case to provide horizontal  
107 observational data where Event-1 lacks coverage. Detailed trajectories of these two launches were  
108 not available; therefore, we derived the trajectories based on the rocket depletion observations by  
109 Park et al. (2015, 2016) and the Atlas-V user manual, as depicted in Figure 1c. The launch  
110 information and Atlas-V user manual can be accessed from the ULA website:  
111 <https://www.ulalaunch.com/missions>.

### 112 **2.2 Data and Methods**

113 The Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) radio  
114 occultation data have been widely applied in studies of the atmosphere, climate, and ionosphere.  
115 The gridded data products derived from COSMIC occultation observations have been used in  
116 rocket-induced depletion (RED) studies (Park et al., 2022). Moreover, COSMIC occultation data  
117 are frequently employed to monitor and investigate ionospheric disturbances caused by special  
118 events such as earthquakes, tsunamis, and sporadic Es layers (Astafyeva et al., 2011; Arras &  
119 Wickert, 2017; Yan et al., 2018, 2020, 2022; Qiu et al., 2021). A detailed assessment of the  
120 feasibility and reliability of COSMIC radio occultation data can be found in Lei et al. (2007) for

121 COSMIC-1 and in Lin et al. (2020) for COSMIC-2.. In this study, we utilize the electron density  
 122 and total electron content (TEC) data derived from COSMIC-1 occultations (Level 1b, 1/60 Hz;  
 123 product identifiers: ionPhs\_repro and podTec\_repro) to identify electron density depletions  
 124 induced by rocket exhausts and to determine their corresponding altitude information. The  
 125 COSMIC-1 datasets are provided by the COSMIC Data Analysis and Archive Center (CDAAC)  
 126 and are available at <https://data.cosmic.ucar.edu/gnss-ro/>.

127 To investigate the horizontal spatial distribution of the REDs, we used data from ground-based  
 128 GNSS receivers. The vertical total electron content (TEC) was calculated following the method  
 129 described by Yan et al. (2017). The GNSS receiver data were obtained from the SOPAC & CSRC  
 130 database service website (<http://garner.ucsd.edu/>). The ionospheric total electron content (TEC),  
 131 defined as the total number of electrons integrated along the signal path I (unit:  $m^{-2}$ ,  $10^{16} m^{-2} = 1$   
 132 TECU), was derived from dual-frequency GPS carrier phase (L1/L2) and pseudorange (P1/P2)  
 133 measurements. The computation was based on the ionospheric refraction model proposed by  
 134 Klobuchar (1991):

$$135 \quad STEC_L = \left[ \left( \frac{f_2^2}{f_1^2 - f_2^2} \right) \frac{f_1^2}{40.3} \right] (L_1 \lambda_1 - L_2 \lambda_2) \quad (1)$$

$$136 \quad STEC_P = \left[ \left( \frac{f_2^2}{f_1^2 - f_2^2} \right) \frac{f_1^2}{40.3} \right] (L_1 \lambda_1 - L_2 \lambda_2) \quad (2)$$

$$137 \quad STEC = STEC_P + \sqrt{\sum_{i=1}^N (STEC_L - STEC_P)^2 / N} \quad (3)$$

138 where  $f_1$  and  $f_2$  are GPS signal frequencies at 1.57542 GHz and 1.2276 GHz, respectively;  $\lambda_1$  and  
 139  $\lambda_2$  are the corresponding wavelengths; N is the number of measurements sampled during a satellite  
 140 pass.

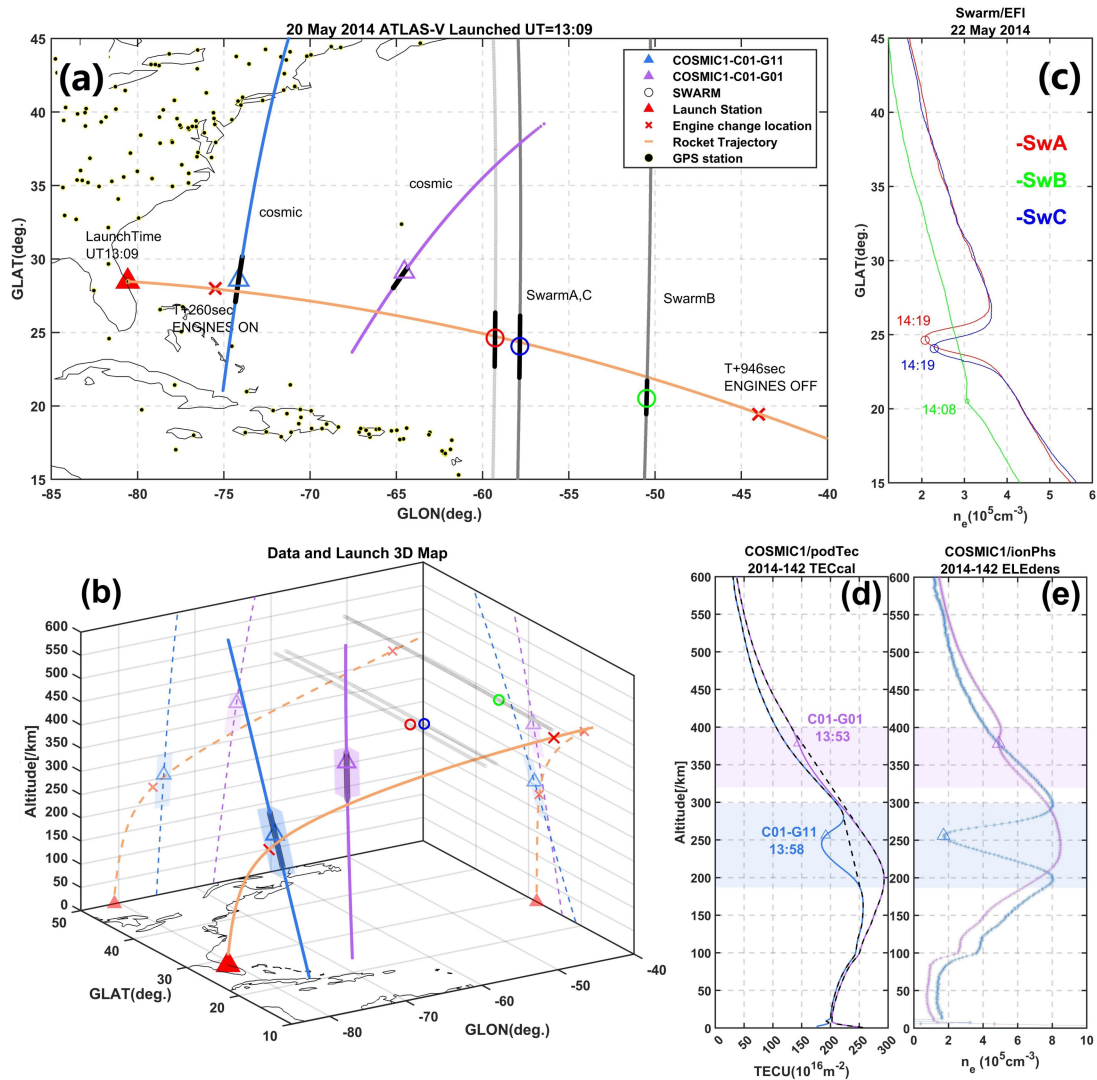
141 The calculated STEC was projected onto the sub-ionospheric point (SIP) on the Earth's surface  
 142 using an ionospheric single-layer model. The vertical TEC (VTEC) can then be derived from the  
 143 following equation (Jin et al., 2008):

$$144 \quad VTEC = (STEC - B^S - B_R) \times \sqrt{1 - \left( \frac{r_e \cos \theta}{r_e + h_{ion}} \right)^2} \quad (4)$$

145 where  $B^S$  and  $B_R$  are the instrumental biases related to GPS satellites and receivers, respectively;  $r_e$   
 146 = 6371 km is the mean radius of the Earth;  $\theta$  is the elevation angle of a GPS satellite;  $h_{ion}$  is the  
 147 height of the single ionosphere model, 350 km in this study. Below we use the TEC in place of  
 148 VTEC for convenience.

149 Based on the TEC data, the identification method proposed by Pradipta et al. (2015) for  
 150 ionospheric plasma bubbles was adopted and optimized using a third-order polynomial fitting to  
 151 capture the specific characteristics of REDs. This approach allows for a more accurate extraction  
 152 of the absolute vertical TEC depletion values and provides a clearer representation of the  
 153 horizontal distribution features of the REDs.

154 The Swarm constellation, comprising three satellites at orbital altitudes of 450-550 km, is  
 155 equipped with Langmuir probes to measure electron density, enabling the observation of REDs.  
 156 Park et al. (2016) first reported Swarm observations of REDs, with detailed descriptions of the  
 157 instruments and data available in their study. The Swarm data are sourced from the European  
 158 Space Agency (ESA): <https://swarm-diss.eo.esa.int/#swarm>.



159

160 **Figure 1. Observation Data Distribution and Details.** (a) Map of rocket launch data distribution: the orange  
 161 line represents the rocket trajectory, the red triangle marks the launch site, the red "x" indicates the start  
 162 and end points of the rocket's second-stage engine working; The projection of COSMIC observation  
 163 location points are shown as blue and purple lines, with triangular markers indicating detected depletion  
 164 locations. The red/green/blue symbols represent REDS center observed by Swarm-Alpha/Bravo/Charlie, the  
 165 gray dashed lines their trajectories. (b) 3D rocket trajectory (geographic projections) with COSMIC  
 166 puncture-line shading indicating depletion extents. (c) Electron density measurements from Swarm satellites,  
 167 with UT time at each marked point. (d) COSMIC TEC profile, with shaded REDS region and corresponding  
 168 UT time. (e) COSMIC electron density profile.

169 **2.2 Simulation of RED**

170 The formation of ionospheric electron density depletion is closely linked to the diffusion patterns  
 171 and chemical reactions of rocket-exhaust (e.g. Bowden et al., 2020; Zhao et al., 2024). Previous  
 172 studies have shown that releasing around 4 kg of water vapor at 210 km altitude can cause  
 173 significant depletions, with the affected area expanding at higher altitudes (e.g. Hu et al., 2010,  
 174 2011, 2013; Huang et al., 2011). Factors like release trajectory, exhaust flow rate, source speed,  
 175 geomagnetic declination, and background winds further influence depletion patterns (e.g. Zhao et  
 176 al., 2016; Feng et al., 2017; Gao et al., 2021). In this study, we also incorporate the effects of  
 177 daytime electric fields and photoionization to improve simulation accuracy.

178 Rocket launches consume up to 79% of their fuel below 80 km altitude, representing the  
 179 predominant portion of total fuel consumption (Barker et al., 2024). The ATLAS-V first-stage core  
 180 carries 284 tons of fuel, with boosters attached to it, while the second stage carries 20.83 tons. The  
 181 first stage alone accounts for over 93% of the total fuel load. As it releases most exhaust in the  
 182 lower atmosphere and below the ionospheric D-region, the influence of first-stage exhaust on the  
 183 REDs analyzed in this study is negligible. We selected the second stage ignition (~260 seconds  
 184 after launch at ~200 km altitude) as the starting point of a 684-second exhaust release. The  
 185 second-stage engine thrust for the ATLAS-V is approximately 22,890 lbs (equivalent to 10,382.73  
 186 kg), with a specific impulse ( $I_{sp}$ ) of 449.7 seconds. Based on the standard formula relating thrust,  
 187 specific impulse, and exhaust flow rate(Feng et al., 2021):

$$I_{sp} = \frac{F}{g_0 \dot{m}} \quad (5)$$

188 where  $I_{sp}$  is the specific impulse,  $F$  represents thrust, and  $\dot{m}$  is the released flow rate. The mass  
 189 flow rate is calculated to be approximately 23.08 kg/s. Assuming a 5.5:1 oxidizer-to-fuel ratio, the  
 190 mass fraction of water vapor in the exhaust is estimated to be ~95%, and hydrogen ~5%(Mendillo  
 191 et al., 1975).

192 The diffusion equation proposed by Bernhardt (1976) for neutral material release calculates the  
 193 molecular density of a point source as:

$$\begin{aligned} n(x, y, z, t) = & \frac{N_0}{(4\pi D_0 t)^{1.5}} \exp\left\{-(z - z_0) \left( \frac{3}{4H_a} + \frac{1}{2H_r} \right) \right. \\ & - \frac{H_a^2 \{-(z - z_0)/(2H_a)\}^2}{D_0 t} - \beta t \\ & - \frac{(x^2 + y^2) \exp[-(z - z_0)/(2H_a)]}{4D_0 t} \\ & \left. - \left( \frac{1}{H_a} - \frac{1}{H_r} \right)^2 \frac{D_0 t \exp[(z - z_0)/(2H_a)]}{4} \right\} \end{aligned} \quad (6)$$

194  $D_0$  is the diffusion coefficient follows Mendillo (1993);  $H_a$  and  $H_r$  ( $H=kT/mg$ ) are the atmospheric  
 195 scale heights for air and the release substance, respectively;  $z_0$  is the release altitude; where  $\beta$  is a  
 196 loss coefficient that includes chemical reactions and photoionization.

197 The diffusion coefficient ( $D_0$ ) is a key parameter controlling the temporal evolution and spatial  
 198 distribution of neutral species. It depends on the molecular number density and ambient  
 199 temperature of the background atmosphere at the release altitude. In the ionospheric region, the  
 200 dominant neutral constituents are atomic oxygen (O), molecular nitrogen (N<sub>2</sub>), and molecular

201 oxygen (O<sub>2</sub>). The diffusion coefficients of the released species, such as H<sub>2</sub>O and H<sub>2</sub>, are calculated  
 202 following the method of Mendillo (1993), and can be expressed in a simplified form as:

$$203 \quad D_{\text{H}_2\text{O}} = \left[ \frac{n_{\text{O}}}{8.46 \times 10^{17} T_n^{0.5}} + \frac{n_{\text{N}_2}}{2.04 \times 10^{17} T_n^{0.632}} + \frac{n_{\text{O}_2}}{2.02 \times 10^{17} T_n^{0.632}} \right]^{-1} \text{cm}^2 \cdot \text{s}^{-1} \quad (7)$$

$$204 \quad D_{\text{H}_2} = \left[ \frac{n_{\text{O}}}{2.97 \times 10^{18} T_n^{0.5}} + \frac{n_{\text{N}_2}}{2.8 \times 10^{17} T_n^{0.740}} + \frac{n_{\text{O}_2}}{3.06 \times 10^{17} T_n^{0.732}} \right]^{-1} \text{cm}^2 \cdot \text{s}^{-1} \quad (8)$$

205 Where  $n_{\text{O}}n_{\text{N}_2}n_{\text{O}_2}$  denotes the number densities of O, N<sub>2</sub>, and O<sub>2</sub>, and T<sub>n</sub> is the neutral  
 206 atmospheric temperature.

207 By moving point sources along the rocket trajectory, we simulate continuous rocket exhaust  
 208 diffusion (e.g. Zhao et al., 2016; Feng et al., 2021). H<sub>2</sub>O and H<sub>2</sub> released into the ionosphere  
 209 mainly participates in the following reactions as table-1, to deplete ionospheric electrons:

210 Table-1 The main chemical equations involved in the simulation release.

Species	Reaction Equation	Reaction Ratio $\text{cm}^3 \cdot \text{s}^{-1}$	Reference
H <sub>2</sub>	$\text{H}_2 + \text{O}^+ \xrightarrow{k_1} \text{OH}^+ + \text{H} + 0.35\text{eV}$	$k_1 = 1.7 \times 10^{-9}$	Ferguson ., 1973
	$\text{OH}^+ + \text{e}^- \xrightarrow{k_2} \text{O}^* + \text{H} + 8.74\text{eV}$	$k_2 = 7.5 \times 10^{-8} [300/T_e]^{0.5}$	Bernhardt ., 1987
	$\text{OH}^+ + \text{H}_2 \xrightarrow{k_3} \text{H}_2\text{O}^+ + \text{H} + 1.21\text{eV}$	$k_3 = 1.5 \times 10^{-9}$	Fehsenfeld et al., 1967
H <sub>2</sub> O	$\text{H}_2\text{O} + \text{O}^+ \xrightarrow{k_4} \text{H}_2\text{O}^+ + \text{O} + 1.01\text{eV}$	$k_4 = 3.2 \times 10^{-9}$	Smith et al., 1978
	$\text{H}_2\text{O} + \text{e}^- \xrightarrow{k_5} \text{OH}^* + \text{H} + 7.45\text{eV}$	$k_5 = 6.5 \times 10^{-7} [300/T_e]^{0.5}$	Bernhardt ., 1978
	$\text{H}_2\text{O} + \text{H}_2\text{O}^+ \xrightarrow{k_6} \text{H}_3\text{O}^+ + \text{OH} + 1.17\text{eV}$	$k_6 = 1.67 \times 10^{-9}$	Bolden and Twiddy., 1972
	$\text{H}_3\text{O}^+ + \text{e}^- \xrightarrow{k_7} \begin{cases} \text{H}_2\text{O} + \text{H} + 6.29\text{eV} \\ \text{OH}^* + \text{H}_2 + 5.36\text{eV} \end{cases}$	$k_7 = 6.3 \times 10^{-7} [300/T_e]^{0.5}$	Heppner et al., 1976

211 k<sub>1</sub> - k<sub>7</sub> represent chemical reaction rates; T<sub>e</sub> is electron temperature. Based on the methodology of  
 212 Mendillo et al. (1993), the electron density variation per time step Δt resulting from chemical  
 213 reactions of the type  $A+B \xrightarrow{k_i} C+D$  (where k<sub>i</sub> represents the reaction rate coefficient) is calculated.  
 214 The expression for the concentration changes of reactants and products involved in the reaction  
 215 per time step Δt is given as:

$$\Delta n_i = k_i \cdot n_A \cdot n_B \cdot \Delta t \quad (9)$$

216 Neutral release disrupts ionospheric equilibrium, inducing plasma diffusion. Assuming the  
 217 dominant influence of the geomagnetic field, plasma diffusion is primarily motion along magnetic  
 218 field lines, with its continuity equation expressed as:

$$\frac{\partial n_p}{\partial t} = -\nabla \cdot (n_p \vec{v}_\perp + n_p \vec{v}_\parallel) + P_p - L_p \quad (10)$$

219 Where n<sub>p</sub> is charged particle density distribution, P<sub>p</sub> and L<sub>p</sub> are particle production and loss terms;  
 220 v<sub>∥</sub> and v<sub>⊥</sub> are the velocity vector parallel and perpendicular to the magnetic field. Geomagnetic  
 221 inclination (I) and declination (φ) define the field direction, with s along the magnetic field line.  
 222 Plasma diffusion speed along the magnetic field is expressed as:

$$v_{\parallel} = -D_p \left[ \frac{\partial \ln(n_p T_p)}{\partial s} + \frac{\sin I}{H_p} \right] + v_D \quad (11)$$

$$v_{\perp} = \frac{\vec{E} \times \vec{B}}{B^2} + \frac{m \vec{g} \times \vec{B}}{q B^2} \quad (12)$$

223  $D_p$  is the plasma diffusion coefficient,  $D_p=(1+T_e/T_i)D_i$ , where  $D_i$  is the ion diffusion coefficient;  
 224  $T_p$  is plasma temperature,  $T_p=(T_i+T_e)/2$ ;  $H_p$  is the plasma scale height,  $H_p=k(T_e+T_i)/m_i g$ ;  $v_D$   
 225 represents external drift velocity;  $\vec{g}$  is gravitational acceleration, and  $q$  is the ion charge. The  $\vec{E} \times \vec{B}$   
 226 drift velocity term for  $v_{\perp}$  is provided by Anderson (1978). Based on these equations, the plasma  
 227 diffusion formula in a Cartesian coordinate system (x-east, y-north, z-up) is:

$$\begin{aligned} \frac{\partial n_p}{\partial t} = & \sin^2 I \cdot \left[ \frac{\partial D_p}{\partial z} \frac{\partial n_p}{\partial z} + \frac{n_p}{T_p} \frac{\partial D_p}{\partial z} \frac{\partial T_p}{\partial z} + \frac{n_p}{H_p} \frac{\partial D_p}{\partial z} + \frac{D_p}{T_p} \frac{\partial n_p}{\partial z} \frac{\partial T_p}{\partial z} + \frac{D_p}{H_p} \frac{\partial n_p}{\partial z} + \right. \\ & \left. D_p n_p \frac{\partial (1/H_p)}{\partial z} - \frac{D_p n_p}{T_p^2} \left( \frac{\partial T_p}{\partial z} \right)^2 + \frac{D_p n_p}{T_p} \frac{\partial^2 T_p}{\partial z^2} \right] + \sin^2 I \cdot D_p \frac{\partial^2 n_p}{\partial z^2} - v_D \sin I \frac{\partial n_p}{\partial z} \\ & + \cos^2 I \sin \varphi \cdot D_p \frac{\partial^2 n_p}{\partial x^2} + \sin I \sin \varphi \frac{D_p}{H_p} \frac{\partial n_p}{\partial x} - v_D \cos I \sin \varphi \frac{\partial n_p}{\partial x} \\ & + \cos^2 I \cos \varphi \cdot D_p \frac{\partial^2 n_p}{\partial y^2} + \sin I \cos \varphi \frac{D_p}{H_p} \frac{\partial n_p}{\partial y} - v_D \cos I \cos \varphi \frac{\partial n_p}{\partial y} + P - L + v_{\perp} \nabla n_p \end{aligned} \quad (13)$$

228 The numerical model, built upon the above theoretical framework, simulates the launch scenario  
 229 of Event 1 using a central finite-difference scheme. Table 2 summarizes the background models  
 230 and simulation parameters.

231 Table 2 Parameter settings and background model for numerical simulation.

Num	parameter	value
1	Release time	UT 2014-May-22 13:09
2	Location and grid count	31.03°N to 19.29°N, 49.80°W to 77.01°W; Long grids=300; Lat grids = 130;
3	Altitude	100-600 km; dz = 2 km, Grids = 250
4	Time step	0.01s
5	Rate of release	H <sub>2</sub> O: 21.9722 kg/s & H <sub>2</sub> : 1.1078 kg/s
6	Speed of release position	3.1-5.9 km/s
7	Background ionosphere	IRI-2016
8	Background magnetic field	IGRF-13
9	Atmosphere density and gas temperature	ATMOSNRLMSISE-00

## 232 3 Result and Discussion

### 233 3.1 Observation

234 Figure 1(a,b) presents the rocket trajectory and observed depletion locations for Event-1. Figure  
 235 1(d,e) presents the vertical profiles of TEC and electron density from COSMIC-1 satellite C01  
 236 paired with navigation satellites G01 and G11, labeled as C01-G11 and C01-G01. Both radio  
 237 occultation events occurred within 10 minutes, with triangular markers indicating the depletion  
 238 centers and corresponding UT timestamps. For the C01-G11 at UT 13:58, about 40 minutes after  
 239 the ATLAS-V rocket's second-stage ignition, depletion was observed between 197-300 km

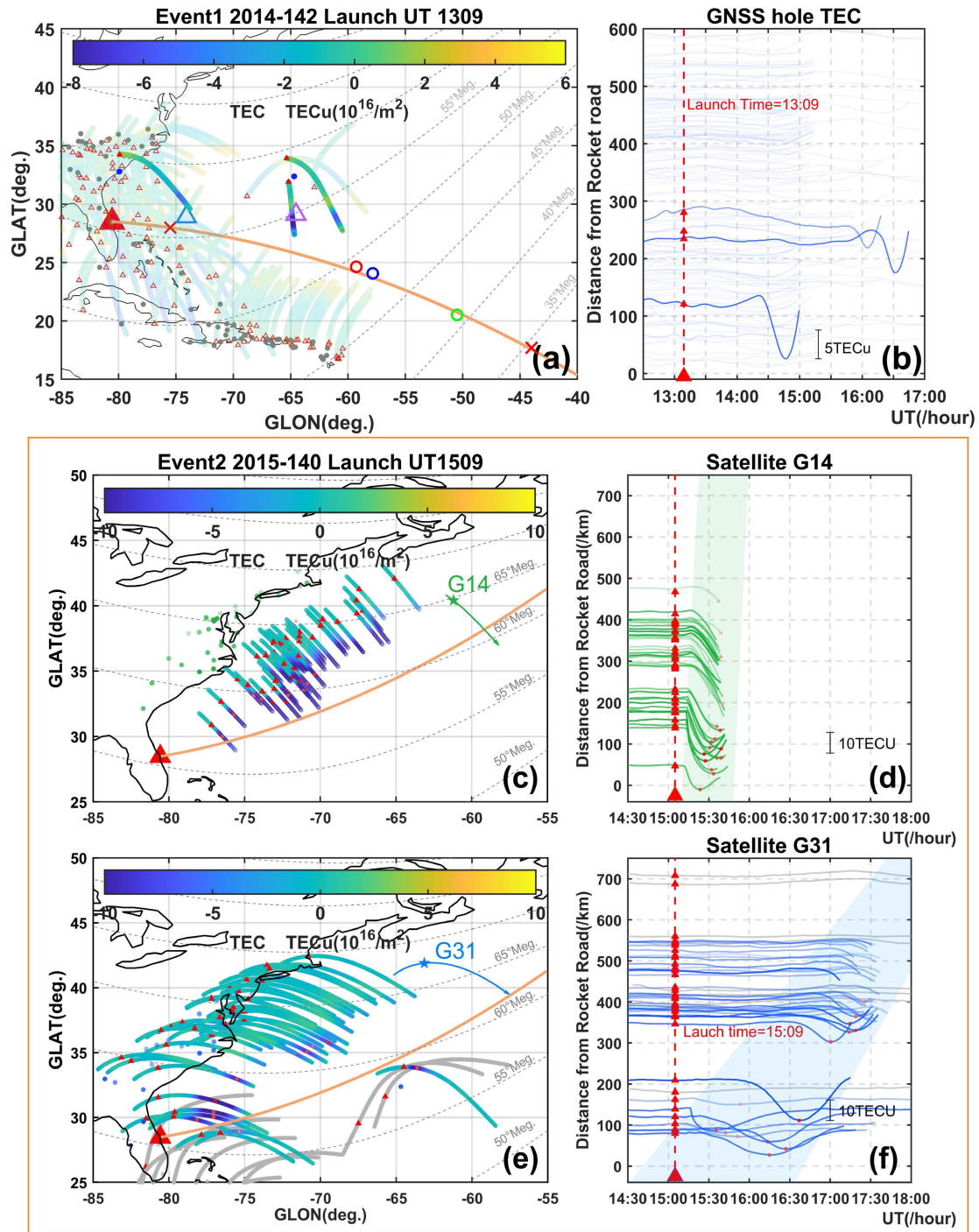
240 altitude, showing a maximum TEC drop of  $\sim 50$  TECU and an electron density reduction of  $\sim 75\%$   
241 at 250 km. The C01-G01 at UT 13:53 recorded depletion between 310-400 km, with an electron  
242 density  $\sim 15\%$  reduction at 375 km. The lower boundary, estimated using Pradipta et al. (2015),  
243 was between 250–320 km for C01-G01. Because the vertical profiles of occultation data not only  
244 record altitude information but also extend along the north-south direction across several thousand  
245 kilometers, an occultation ray may intersect the horizontal extent of the REDs region. Therefore,  
246 the upper and lower boundaries observed in occultation profiles do not necessarily represent the  
247 true vertical limits of the REDs. Furthermore, due to the asymmetric vertical distribution of REDs,  
248 the upper and lower boundaries of the depletion vertical scale derived from COSMIC radio  
249 occultation observations are subject to certain errors. Additionally, low-Earth-orbit occultation  
250 measurements are influenced by atmospheric refraction, leading to altitude-dependent spatial  
251 uncertainties. At the hmF<sub>2</sub> altitude, the average deviation is approximately 33 km (Xu et al., 2010).  
252 Consequently, the altitude distribution of REDs derived from COSMIC occultation data contains  
253 uncertainties on small spatial scales.

254 As supporting evidence, these REDs were previously reported by Park et al. (2015, 2016) using  
255 Swarm in-situ measurements, which are also retrieved in this study (Figure 1c).  
256 Swarm-Alpha/Bravo/Charlie are marked in different colors, with times of minimum depletion  
257 labeled. The Swarm observations occurred around UT 14:00. Altitudes are shown in Figure 1c,  
258 where Swarm A and C orbited at 469.9 km, and Swarm B at 518.5 km. The north-south REDs  
259 lengths recorded by Swarm A, C, and B were 419 km, 491 km, and 277 km, respectively, with  
260 maximum electron density reductions of about 45%, 39%, and 5%. The horizontal distribution of  
261 REDs measured by Swarm closely followed the rocket's projected ground track.

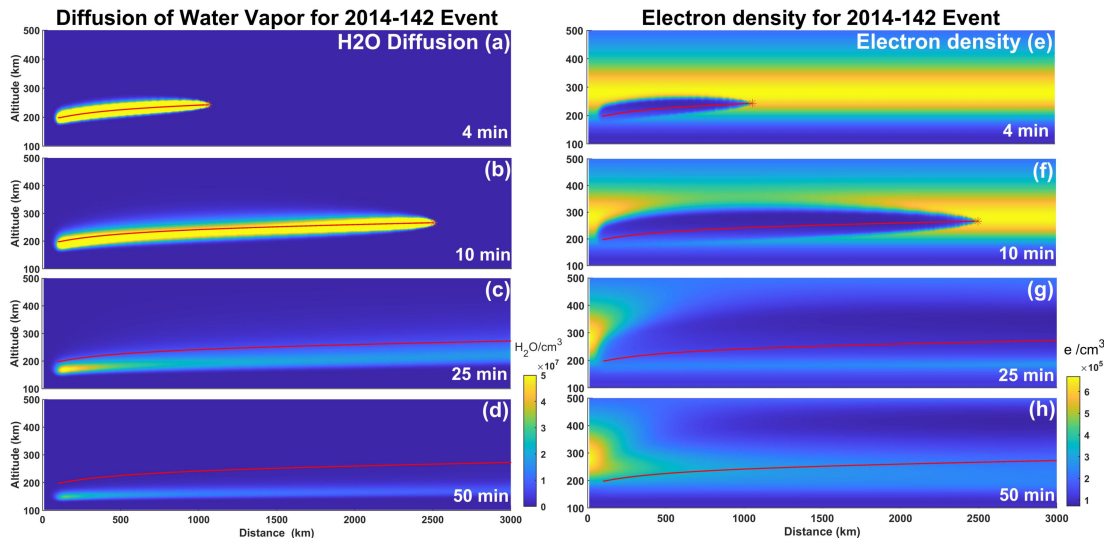
262 Figure 2 presents the REDs characteristics extracted from ground-based GNSS TEC data for  
263 Event-1 and Event-2. Figure 2a shows the GNSS data distribution for Event-1, Figure 2b shows  
264 the corresponding time series of the identified REDs in differential TEC (DTEC). The vertical axis  
265 is arranged according to the closest distance from the observation points to the rocket trajectory,  
266 indicating the observed REDs' distance from the rocket path. Due to the offshore launch and  
267 limited temporal coverage, most GNSS data failed to capture the REDs. Some ionospheric  
268 piercing points (IPPs) near the second-stage ignition site and occultation region didn't capture  
269 RED signatures because they arrived 2-3 hours after launch, by which time the RED had drifted  
270 northward out of the area. To improve visualization, the data points without detected REDs  
271 signatures are semi-hidden. Figure 2a also shows the horizontal TEC distribution map, where red  
272 small triangles indicate the recording position for each data curve at the launch time, and black  
273 arrows mark the time sequence of data measurement. For Event-1, the GNSS effective observation  
274 data is sparse; the maximum depletion amplitude observed occurred approximately 1.5 hours after  
275 the launch, with a magnitude of about 9 TECU ( $1\text{TECU}=10^{16}/\text{m}^2$ ) at a distance of  $\sim 200$  km  
276 from the rocket trajectory, located near the C01-G01.

277 Due to sparse GNSS coverage along Event-1's rocket trajectory, accurate horizontal depletion  
278 scales could not be determined. Therefore, Event-2 serves as a reference, given the identical rocket  
279 model, similar launch trajectory, and matching local time. Figures 2c-f depict the horizontal TEC  
280 distribution and time-series depletion signals from Event-2. Figures 2c and 2e show the IPPs for  
281 TEC observed at 300 km by the G14 and G31. The corresponding time-series signals in Figure 2d  
282 and Figure 2f are arranged by the shortest distance to the rocket trajectory, similar to Figure 2b.

283 For Event-2, the REDs extended up to ~500 km across the trajectory and exceeded 2000 km in  
 284 length, with a maximum TEC reduction of approximately 20 TECU, lasting over 2 hours.

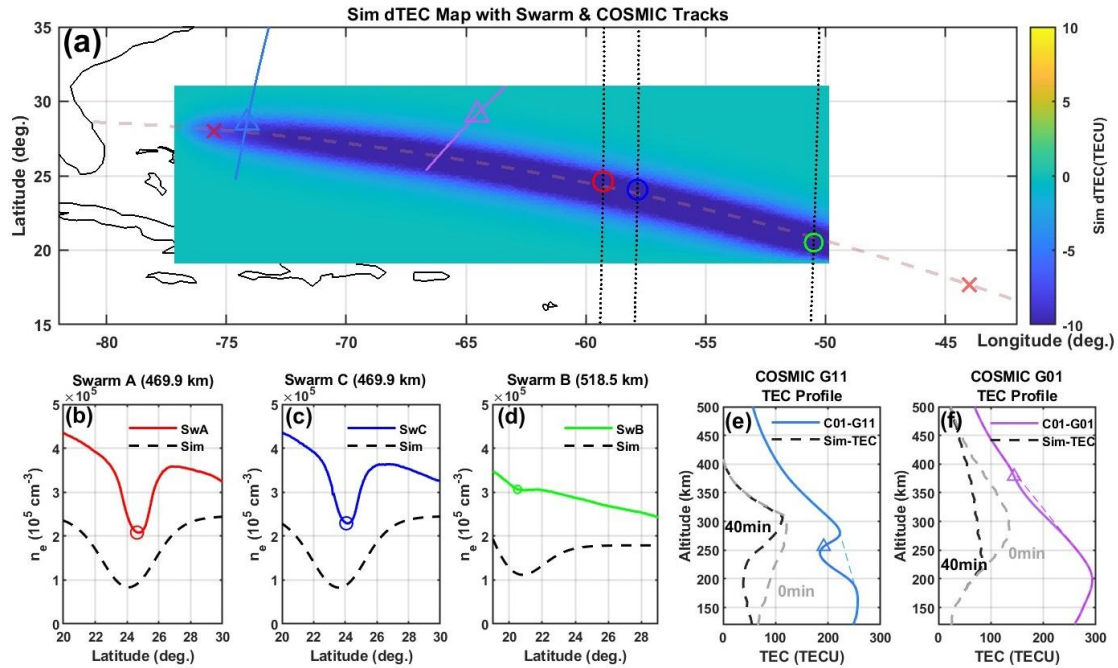


285  
 286 **Figure 2. GNSS TEC data for Event-1 and Event-2. (a, c, e) TEC IPPs maps: the large red triangle marks**  
 287 **the launch site, the orange line shows the rocket trajectory, small red triangles indicate IPPs at launch time,**  
 288 **black arrows show their movement, and color represents depletion magnitude. (b, d, f) Time series of**  
 289 **extracted TEC depletion; red dashed lines mark launch time. (a-b) Event-1: (a) IPPs distribution; (b)**  
 290 **Depletion time series. (c-f) Event-2: (c, e) IPPs from G14 and G31; (d, f) Corresponding depletion time**  
 291 **series.**



293  
 294 **Figure 3. Simulation molecular density distribution of H<sub>2</sub>O and electrons. (a-d) H<sub>2</sub>O molecular density**  
 295 **distribution along the rocket trajectory (height vs. flight distance). (e-h) Electron density distributions along**  
 296 **the rocket trajectory. (a-h) Time (lower-right corners): minutes after second-stage ignition; Red line is**  
 297 **rocket trajectory; Red star is current release position.**

298 Figure 3 shows the simulation result of H<sub>2</sub>O release and electron density depletion for Event1.  
 299 Figure 3 (a-d) illustrates the evolution of H<sub>2</sub>O molecular density along the rocket flight path.  
 300 Water vapor diffuses rapidly within the first few minutes, spreading laterally along the trajectory,  
 301 with a vertical range of around 100 km. Molecular density decreases gradually as diffusion slows,  
 302 reaching maximum spread at about 25 minutes, before gravitational settling pulls it to lower  
 303 altitudes, ceasing its contribution to depletion consistent with Zhao et al. (2024). Figure 3 (e-h)  
 304 shows electron density changes during water release. Depletion forms within 1-2 minutes,  
 305 spreading for about 20 minutes. And depletion mainly extends laterally along the trajectory,  
 306 reaching 180 km upwards and 50 km downwards. Recovery follows, with faster recovery at lower  
 307 altitudes due to higher background density, showing an upward drift pattern consistent with Zhao  
 308 et al. (2024). At 50 minutes, the depletion reaches a thickness of 150-300 km and 200-500 km in  
 309 vertical range. We have included multiple detailed depletion evolution videos in the  
 310 supplementary video materials (sv1.mp4, sv2.mp4, sv3.mp4), which visualize the simulated 3D  
 311 spatiotemporal evolution processes.



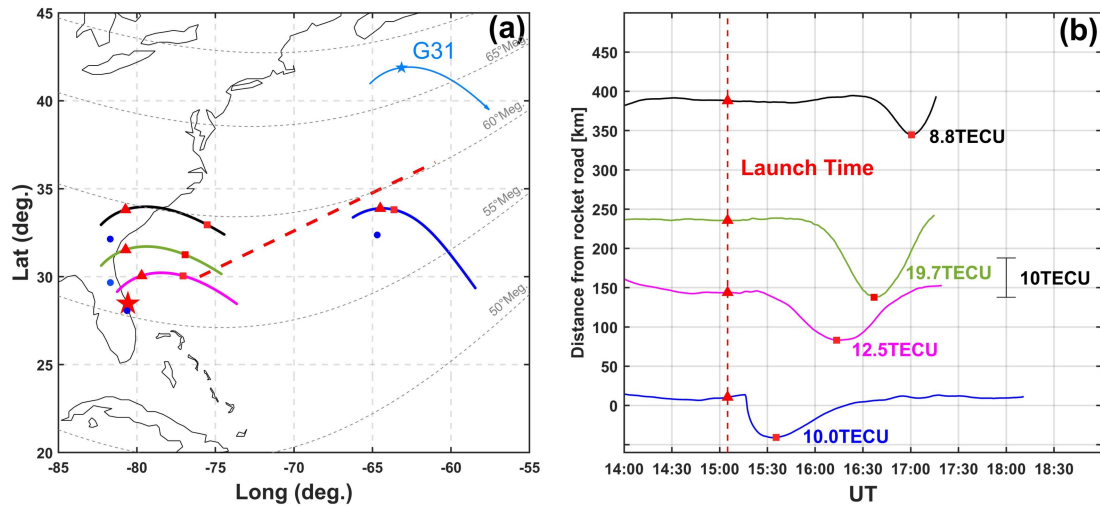
312

313

314 **Figure 4 Comparison of the simulated dTEC calculation at the 40th minute with observational data. (a) The**  
 315 **variation in the vertical integral of the simulated electron density, dTEC; (b–d) Comparison of electron**  
 316 **density between Swarm satellites and simulations; (e–f) Comparison of the integral of electron density along**  
 317 **the simulated COSMIC radio occultation ray path with the podTEC from occultation observations.**

317

318 In the simulation results, Figure 4a shown the distribution of the vertical TEC variation. The  
 319 simulated TEC variation intensity is approximately 10 TECU, and the simulated depletion is  
 320 primarily distributed along the release trajectory, with a horizontal width perpendicular to the  
 321 trajectory of about 500 km. Figures 4(bcd) present a comparison of electron density between the  
 322 Swarm A, Swarm C, and Swarm B satellites and the simulations. The simulation results show that  
 323 at the location corresponding to Swarm A, the electron density reduction amplitude is  $1.6 \times 10^6$   
 324  $\text{cm}^{-3}$  (with an observed reduction of  $1.9 \times 10^6 \text{ cm}^{-3}$ ), and the background change rates are 65.6%  
 325 and 65.7%, respectively, significantly higher than the depletion amplitudes of 45% and 39%  
 326 observed by Swarm A and Swarm C. The background electron density observed by the satellites is  
 327 significantly higher than that output by the IRI model; this discrepancy affects the chemical  
 328 reaction efficiency and extent, representing a primary reason for the differences between the  
 329 simulation and observations. Figures 4(ef) show a comparison between the integral of electron  
 330 density along the simulated COSMIC radio occultation ray path and the podTEC from occultation  
 331 observations. The simulated TEC variation is about 40 TECU, and the depletion altitude ranges  
 332 are 120-305 km and 220-450 km, respectively, which are broader than those observed in the two  
 333 occultation events. The background TEC is significantly lower than the observed values, primarily  
 334 due to the combined effects of the occultation ray path geometry and errors in the background  
 electron density from the IRI model.



336  
 337 **Figure 5. TEC signals of the depletion observed within the REDs at several different time intervals. (a) Map**  
 338 **of piercing points: red triangles indicate the positions of piercing points at the rocket launch time; small red**  
 339 **squares mark the positions where the maximum TEC values of the REDs were recorded; blue circles**  
 340 **represent GPS stations; red pentagrams indicate the rocket launch site; red dashed lines show the central**  
 341 **line of the REDs. (b) Extracted TEC profiles of the depletion: red dashed lines denote the rocket launch time;**  
 342 **red triangles and squares in different shades correspond to the elements shown in the left panel.**

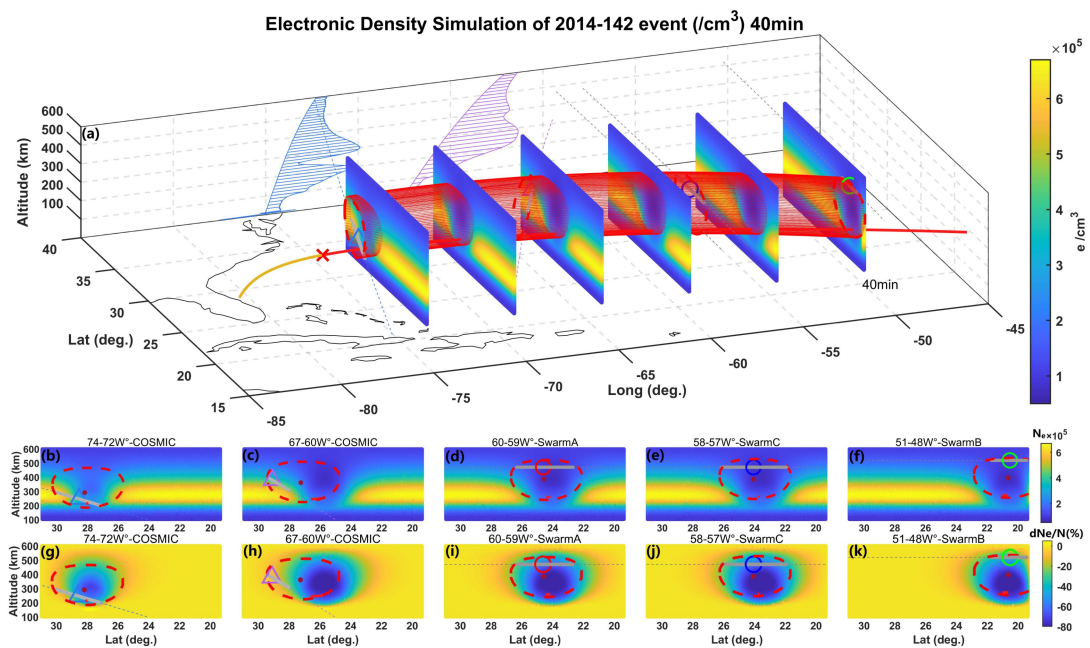
343 The ionospheric piercing points (IPPs) for TEC data derived from ground-based GPS receivers  
 344 shift over time, providing temporal sequences of REDs observations at different intervals. As  
 345 shown in Figure 5, for the IPPs closest to the rocket trajectory (blue line), the TEC begins to drop  
 346 approximately 10 minutes after launch—this 10 mins delay corresponds to the time required for  
 347 the rocket to reach the vicinity of this IPPs. The decrease occurs rapidly within 3-5 minutes,  
 348 followed by a slower decline. Since this location (blue line) is at the edge of the main REDs, the  
 349 maximum depletion amplitude observed here is about 10 TECU, which is weaker than the values  
 350 recorded later by IPPs that pass directly through the depletion (green and pink lines). For IPPs  
 351 entering the REDs more than 20 minutes after launch, the TEC variations exhibit smoother curves.  
 352 The maximum depletion amplitude for this entire event is recorded around 90 minutes post-launch.  
 353 Furthermore, as indicated in Figure 2, most TEC variations observed after 90 minutes are  
 354 collectively weaker than the maximum amplitude captured by the green line. This suggests that  
 355 the REDs subsequently entered a diffusion-driven recovery stage after 90 minutes, gradually  
 356 returning to background levels.

357 The horizontal evolution of REDs in Event-1 is consistent with Event-2 (same rocket type) and  
 358 prior cases (e.g. Mendillo et al.,2008), where depletions exceeded >2000 km in length and ~500  
 359 km in width from the same launch site. The REDs evolution generally follows three stages: (i)  
 360 formation within 5-7 minutes post-launch, with GNSS detecting rapid depletion; (ii)  
 361 diffusion-driven growth over 25-30 minutes, expanding to 500-2200 km in length and 300-500 km  
 362 in width; (iii) gradual recovery lasting over 50 minutes as density returns to background levels  
 363 (e.g., Liu et al., 2018; Ozeki & Heki, 2010; Mendillo et al., 1976, 2008; Zhao et al., 2024).  
 364 Vertical structures were observed by Wand et al. (1984) between 200-500 km in a trajectory  
 365 matching Event-1. Zhao et al. (2024) reported vertical ranges of ~200-700 km and ~202-535 km

366 from two rocket launches, classifying the vertical evolution into generation, diffusion, and  
 367 recovery stages-consistent with horizontal evolution patterns.

368 Simulations show water vapor rapidly diffuses within 1-2 minutes, expand more slowly over ~20  
 369 minutes, and eventually settle into lower atmospheric layers due to gravity; This aligns with  
 370 previous studies (Hu et al., 2010, 2011; Gao et al., 2017; Zhao et al., 2024). The resulting REDs  
 371 exhibit a vertically "top-wide, bottom-narrow" profile, consistent with Gao et al. (2017). This  
 372 structure likely results from: (i) an exponential increase in diffusion coefficients with altitude,  
 373 causing wider upper depletion; (ii) higher lower-altitude electron densities, promoting faster  
 374 recovery and forming a narrower base. This matches Wand et al. (1984) and aligns with  
 375 COSMIC-1 occultation results, confirming the asymmetric vertical structure. GNSS data show  
 376 TEC drops within 5-7 minutes of launch, lasting 1-2 minutes, and diffusing over 500 km in 15-25  
 377 minutes, consistent with simulations (Mendillo, 1976, 2008; Heki & Nakashima, 2010; Bernhardt,  
 378 2008). Simulation began 260 s post-launch (second-stage ignition), showing rapid density drops  
 379 within 2 minutes and peak diffusion at 20 minutes, closely matching GNSS observations. The  
 380 simulated vertical range (200-500 km) matches Swarm-A/C observations at 469 km and  
 381 COSMIC-1 events, while Swarm-B at 518 km, near the edge, recorded only ~5% variation, within  
 382 simulation error margins.

### 383 3.4 The structure of ELE Hole



384  
 385 **Figure 6. Simulated electron density distribution at 40-minute and the range of HIREs. (a) The COSMIC-1**  
 386 **data tangent points (marked by dashed lines) with electron density profile projections on the 40°N vertical**  
 387 **cross-section. The other marks are the same as Figure 1. (b-f) The simulated and observed ranges in**  
 388 **different latitudinal ranges; (g-k) The percentage change in electron density.**

389 Figure 1 shows COSMIC-1 occultation data and rocket data. Previous studies (Park et al., 2015,  
 390 2016) reported similar REDs lasting nearly 6 hours using DMSP satellite data. For Event-1, GNSS  
 391 data measured depletions ~5 TECU even 3.5 hours post-launch, indicating a prolonged lifetime.  
 392 Both COSMIC-1 radio occultation events occurred within 50 minutes after the rocket launch, and

393 the observed depletion regions were located within approximately 300 km of the rocket trajectory.  
 394 This temporal and spatial proximity indicates that the observed ionospheric depletion was very  
 395 likely caused by the rocket launch. For event C01-G11, the TEC depletion was about 50 TECU,  
 396 with a corresponding electron density reduction exceeding 75%; in contrast, event C01-G01  
 397 showed a weaker depletion, with a TEC decrease of about 13 TECU and an electron density  
 398 reduction of less than 20%. Previous studies have shown that the typical uncertainty of podTEC  
 399 data derived from low Earth orbit radio occultation is about 2-3 TECU (Yue, 2011). In comparison,  
 400 the depletion magnitudes observed in these two events are significantly larger than this uncertainty  
 401 range, suggesting that the observed TEC depletions were mainly caused by rocket exhaust.

402 Swarm-A and C, observing along the latter half of the trajectory, detected reductions around 40%.  
 403 Time differences between these four datasets were <30 minutes. The location of maximum  
 404 depletion for C01-G11 was ~110 km horizontally from the trajectory, while that for C01-G01  
 405 exceeded 300 km. This suggests that depletion strength depends on occultation proximity to the  
 406 center. Similarly, Swarm-B at 519 km altitude, near the depletion's edge, recorded ~5% variation,  
 407 while Swarm-A and C at 469 km, closer to the center, observed larger reductions. Multi-distance  
 408 observations aided in positioning the 3D spatial structure of the REDs. However, the occultation  
 409 tangent point reflects both vertical and horizontal variations, so it doesn't directly indicate  
 410 depletion thickness. Since the occultation ray path is aligned east-west, matching the rocket  
 411 trajectory, the associated uncertainty has minimal impact on the RED reconstruction. Therefore,  
 412 the east-west systematic error in occultation observations can be neglected when estimating the  
 413 3D hollow-tube structure.

414 Table 3. The Characteristics of RED by Rocket Launch Events in previous studies; TSLC is  
 415 Taiyuan Satellite Launch Center of China ( 38.5°N, 111.6°E), KSC is Kennedy Space Center of  
 416 USA( 28.5°N, 80.7°W).

Num	Rocket Type	Launch Station	Launch Time (UT)		RED Scale(km) Length*Width	RED life (min)	Reference
			Date	Time			
E-1	LM-4B	TSLC	2013 Dec 9	03:26	1300*450	~120	Liu et al., 2018
E-2	LM-4B	TSLC	2014 Dec 7	03:26	1300*450	~120	
E-3	LM-2D	TSLC	2023 Mar 30	10:50	>1500*~150	--	Xie et al., 2025
E-4	LM-6A	TSLC	2023 Sep 10	04:30	2000*~300	--	
E-5	LM-6A	TSLC	2022 Mar 29	09:05	2600*~300	~126	Zhao et al., 2024
E-6	Titan IV	KSC	2005 Apr 30	00:50	2200*520	--	Mendillo et al., 2008
E-7	Taepodong-1	North Korea	1998 Aug 31	02:30	--*~200	--	Ozeki & Heki, 2010
E-8	Taepodong-2	North Korea	2009 Apr 5	03:07	--*280	--	

417 The observational period of the radio occultation data falls within the first 50 minutes after the  
 418 rocket launch. Relative to the RED's total lifetime of nearly six hours, this observational period  
 419 places the RED in the early stage of its diffusion recovery phase, a period characterized by a  
 420 considerable horizontal extent. According to previous studies summarized in Table 3, the  
 421 horizontal width of the RED ranges from 150 to 520 km, depending on factors such as rocket type  
 422 and launch trajectory. The RED generated by rockets of the same type performing the same orbital  
 423 mission exhibit similar widths. Therefore, the REDs produced by Event-1 and Event-2 can be

424 assumed to have comparable widths, approximately 500 km, which is used as the horizontal  
425 constraint for the three-dimensional RED structure.

426 Figure 6 illustrates the simulated electron density distribution and the estimated spatial extent of  
427 the HIREs constrained by multi-dimensional observational data. The horizontal extent of the  
428 HIREs is constrained by GNSS TEC observations, while the vertical scale is jointly constrained  
429 by COSMIC and Swarm satellite altitude observations. The boundary of the vertical cross-section  
430 of the HIREs derived from numerical simulations is approximately elliptical. Based on the  
431 horizontal and vertical constraints, the ellipse-like boundaries are fitted to the COSMIC radio  
432 occultation and Swarm satellite observations. Polynomial fitting is then used to connect these  
433 boundaries, producing the red dashed tubular volume in Figure 6, representing the observed  
434 HIREs extent. The three-dimensional simulated electron density distribution is displayed in  
435 cross-sectional view as six parallel colored panels in Figure 6. By comparing the simulated HIREs  
436 with the fitted observational HIREs, the horizontal distance between the centers of the simulated  
437 and observed HIREs does not exceed 120 km, and for the COSMIC-1 C01-G11 occultation event,  
438 the distance between the observed and simulated HIREs centers is less than 30 km. The simulated  
439 HIREs is about 20% wider than the observed electron depletion, likely due to discrepancies  
440 between the background parameters used in the simulation and the actual ionospheric conditions.  
441 Differences between IRI model outputs and real ionospheric TEC can exceed 20% (He et al.,  
442 2023). As the HIREs extends over thousands of kilometers, it is subjected to varying background  
443 wind intensities and associated uncertainties at different locations. These variations, in turn,  
444 induce differential HIREs drift distances, resulting in positional discrepancies between the  
445 simulated HIREs centerline and the observed 3D centerline.

446 Combining simulation and observational results, the three-dimensional structure of the REDs is a  
447 “flattened hollow tube” with a wider top. The entire “flattened 3D hollow tube” envelops the  
448 launch trajectory, with the trajectory located closer to the lower side of the tube, resulting in an  
449 asymmetric vertical distribution of the RED along the trajectory. Simulation results indicate that  
450 the width and thickness of the “flattened 3D hollow tube” are primarily controlled by the amount  
451 and altitude of exhaust release and the background electron density distribution. The High-density  
452 area electron density layer is mainly located around 300 km in the ionospheric F1 layer, where  
453 most chemical reactions of the rocket exhaust also occur, positioning the electron density  
454 depletion center near the F1 layer. As atmospheric density decreases with altitude, the diffusion  
455 coefficient of the exhaust increases exponentially with height (Mendillo, 1975), causing upward  
456 diffusion to be faster and forming an upper-wide, lower-narrow, quasi-ellipsoidal shape. Exhaust  
457 released at lower altitudes can also diffuse upward toward the F1 layer, producing stronger  
458 chemical reactions and generating larger amplitude electron density depletions at higher altitudes  
459 along the release trajectory.

460 By integrating the simulated vertical electron density, the equivalent  $v$ TEC as observed by  
461 ground-based GNSS can be obtained. In this study, equivalent observational integrals were also  
462 performed along the ray paths of two COSMIC radio occultation events, and the simulation results  
463 were compared with electron density measurements from the Swarm satellites, as shown in Figure  
464 4. The simulated  $v$ TEC depletion amplitude and spatial scale are generally consistent with  
465 ground-based GNSS observations; the discrepancies between the simulation and Swarm satellite  
466 observations primarily arise from the fact that the background electron density output by the IRI

467 model is significantly lower than the observed values. In the chemical process of depletion  
468 formation, the recombination efficiency ( $\Delta n_i = k_i \cdot n_A \cdot n_A \Delta t$ ) is related not only to the reaction rate  
469 constant  $k_i$  but also to the concentrations of the reacting species. A higher background electron  
470 density leads to a higher chemical recombination efficiency, resulting in a greater magnitude of  
471 electron density loss. The broader depletion range output from the simulation along the occultation  
472 ray path, compared to actual observations, is closely related to the diffusion coefficient of the  
473 released species. The diffusion coefficient is influenced by background atmospheric parameters,  
474 and the atmospheric component concentrations provided by the NRLMSISE model deviate from  
475 actual values, with a root mean square error of approximately 30% and up to 100% in extreme  
476 cases (Doornbos et al., 2008). This deviation affects the diffusion coefficient of the released  
477 species and further influences the concentration distribution of the diffusing species. Additionally,  
478 the IRI model exhibits errors in the background electron density and oxygen ion ( $O^+$ ) conditions,  
479 which further affect the efficiency and extent of the chemical reactions. The diffusion coefficient  
480 varies with altitude and local time, modulated by background atmospheric composition and  
481 temperature; lower atmospheric molecular concentrations or higher temperatures result in faster  
482 diffusion and broader distribution of the released species, leading to larger depletion scales (both  
483 width and thickness), but the accompanying concentration reduction results in a smaller depletion  
484 amplitude. Therefore, the primary mechanisms governing the characteristics of REDs can be  
485 attributed to the diffusion coefficient and background constituent concentrations, both of which  
486 are determined by the background conditions of the exhaust release.

#### 487 **4 Conclusion**

488 This is the first study that utilizes COSMIC-1 occultation data to resolve the vertical structure of  
489 REDs, integrates Swarm and GNSS-TEC observations, and reconstructs its 3D hollow tube  
490 morphology. Observation-simulation comparisons validate model reliability and support a  
491 three-stage RED evolution framework: rapid formation, diffusion-driven growth, and recovery.  
492 The main conclusions are as follows:

- 493 1. Using COSMIC-1 radio occultation data, we for the first time observed the vertical distribution  
494 of REDs at different locations along the rocket trajectory. At a location 700 km from the launch  
495 site, the RED vertical extent is 197-300 km, while at another location 2600 km away, the observed  
496 vertical extent is 310-400 km.
- 497 2. By combining multi-dimensional observational data with three-dimensional numerical  
498 simulations, we reconstructed the three-dimensional tubular structure of the RED. Its vertical  
499 cross-section is an upper-wide, lower-narrow quasi-elliptical shape, with a vertical-to-horizontal  
500 thickness-to-width ratio of approximately 1:2. The horizontal width of the RED is mainly  
501 controlled by the amount and altitude of rocket exhaust release.
- 502 3. Based on observations and simulations, the evolution of rocket-exhausted ionospheric electron  
503 density depletion can be divided into three stages: rapid formation, diffusive growth, and diffusive  
504 recovery. During the first 3-5 minutes after exhaust release, the REDs undergoes rapid growth,  
505 with the fastest rate of electron density decrease. It then enters a 15-30 minute diffusive growth  
506 stage, during which the REDs expands to its maximum spatial extent, with a vertical thickness  
507 ranging from 100-500 km and a horizontal width along the trajectory of 300-500 km. Finally, the  
508 REDs evolves into the diffusive recovery stage, lasting more than 50 minutes, longer than the

509 preceding two stages. During this stage, the REDs slowly returns to background values while  
510 undergoing drift motions at different rates due to the influence of the magnetic field and  
511 background wind.

512 Due to the influence of factors such as local time, propellant characteristics, and orbital insertion,  
513 understanding of REDs' 3D evolution remains limited. Broader observational coverage and more  
514 diverse cases are needed to identify common patterns and better assess REDs' physical drivers and  
515 space weather impacts.

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522 Data Analysis and Archive Center (CDAAC) at <https://data.cosmic.ucar.edu/>. Swarm satellite data  
523 were obtained from the European Space Agency's Earth Online Swarm Dissemination Server  
524 (<https://swarm-diss.eo.esa.int/>), and we thank ESA for making these data available.

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