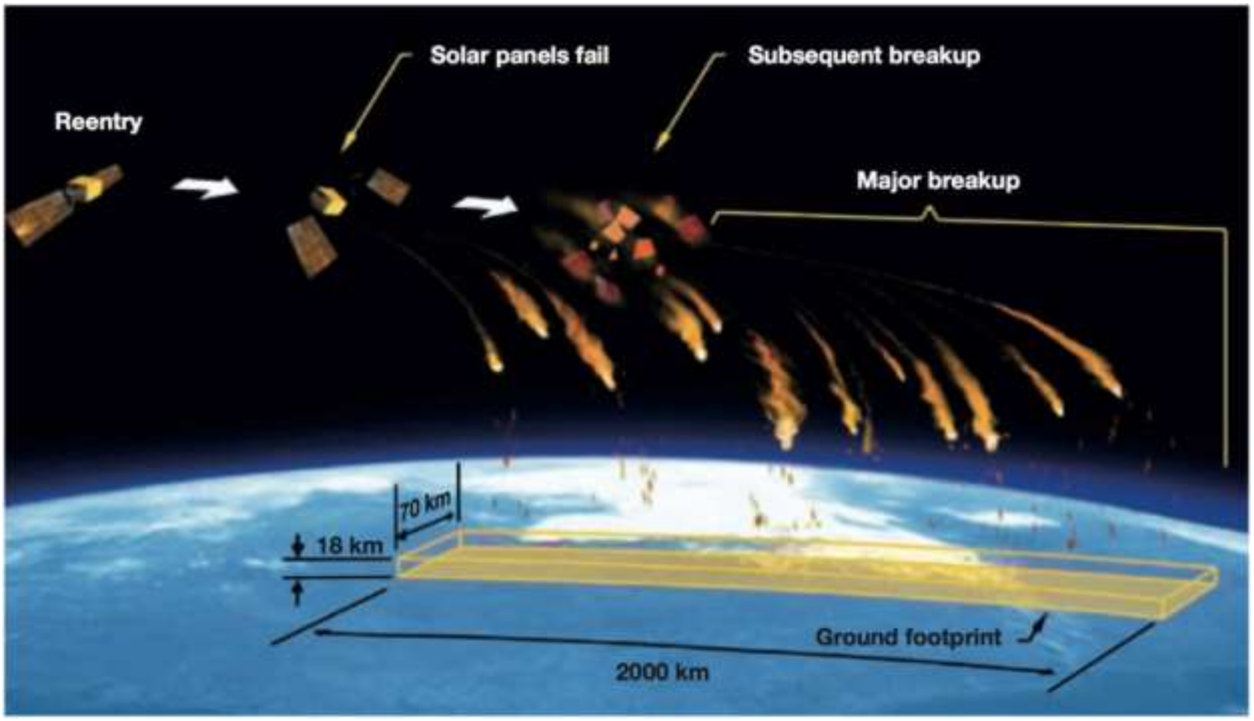

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Ionospheric Reentry of LEO Satellites Impacts GPS Accuracy: Teaching Introductory Plasma Physics to STEM K-12 Students[1]

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Abstract
K-12 students will learn the Earth's atmosphere that they breathe is minimally represented but consists of layers of distinct composition and effects. The ionosphere is one such layer consisting of a distinct plasma medium revealing neutrals, ions, and electrons. While the ionospheric plasma density is typically an order of magnitude (or more) lower than the atmosphere students are familiar with, its characteristic neutral gas density, electrostatic charging leads to the formation of plasma sheath and wake structures around satellites as they descend from Lower Earth Orbit (LEO) on re-entry into Earth's atmosphere. Plasma and the formation of plasma sheath are important topics students will learn when they begin to study the Earth's Moon and early lunar operations of robotic landers and rovers. Global Positioning System (GPS)/ Global Satellite Navigation System (GNSS)communications students utilize rely on the accuracy of satellite transmission and reception of radio wave signals. SpaceX operations have been pivotal in GPS technology development and global coverage. With greater constellations of 300+ satellites being launched into LEO, their eventual demise and atmospheric re-entry entail plasma perturbations that will impact radio wave trajectories. This paper investigates how such perturbations affect radio waves and how they are monitored.
Keywords: Ionosphere, Global Positioning System (GPS)/ Global Satellite Navigation System (GNSS), Satellite re-entry, radio wave, total electron content (TEC)

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Background

Upwards of a 100 km altitude lies the boundary between Earth's atmosphere and space, where the density of air exponentially decreases and many satellite constellations orbit. One of these constellations is Starlink, which provides satellite internet to customers on Earth. In February 2022, a pair of geomagnetic storms stuck Earth shortly after the launch of 49 Starlink satellites, heating the upper atmosphere and causing its density to drastically increase. The higher air density at the initial staging altitude of Starlink caused fatal drag conditions for 38 of the spacecrafts, resulting in their destruction a few days later. Drag is a force acting opposite to the direction of satellite motion, thus slowing it down. Although LEO air density is much lower than near the Earth's surface, air resistance is still strong enough to produce drag and pull satellites on reentry closer to the Earth.

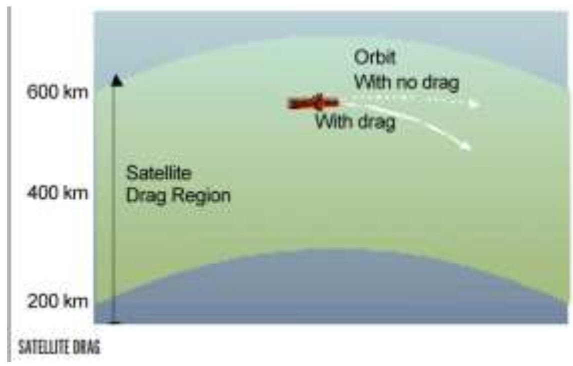

Figure 1 the region of the Earth's atmosphere where atmospheric drag is an important factor perturbing spacecraft orbits (NASA/GSFC)

Furthermore, interactions between the solar wind and the Earth's magnetic field during geomagnetic storms produced large short-term increases in upper atmosphere temperature and density, increasing drag on satellites and changing their orbits. The North American Aerospace Defense Command (NORAD) had to re-identify hundreds of objects and record their new orbits after a large solar storm event (Figure 2). During the March 1989 storm event, for example, NASA's Solar Maximum Mission (SMM) spacecraft was reported to have "dropped as if it hit a brick wall" due to the increased atmospheric drag.

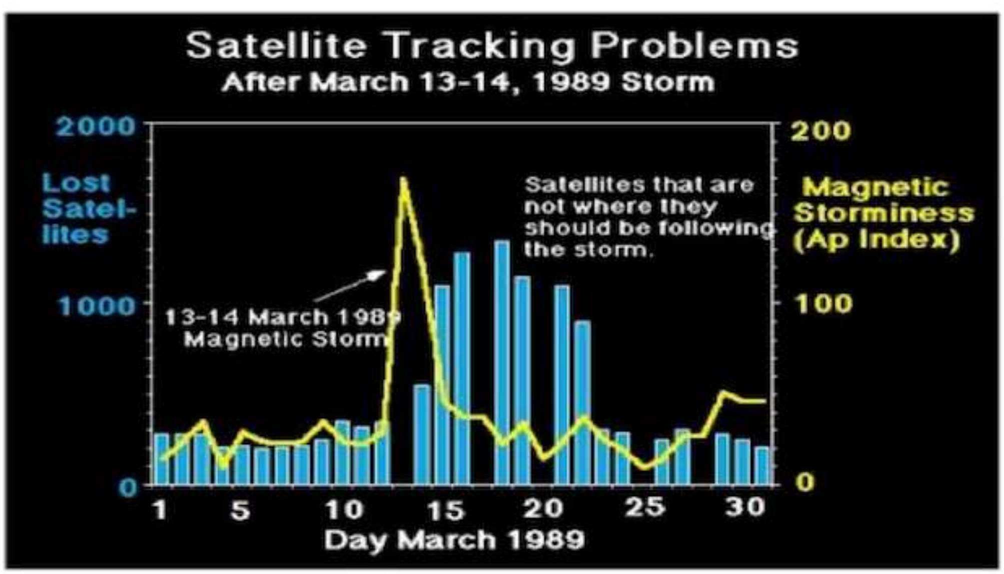

Figure 2. *Number of satellites lost in connection with the March 13-14, 1989 storm (UCAR).*

Introduction

The ionosphere is a layer of weakly ionized plasma bathed in Earth's geomagnetic field extending about 50–600 kilometers above Earth [1]. Ionized by solar radiation, the ionosphere plays an important role in atmospheric electricity and forms the inner edge of the magnetosphere [2]. It has practical importance because, among other functions, it influences radio propagation to distant places on Earth [3]. The velocity of radio waves changes when the signal passes through the electrons in the ionosphere. The total delay suffered by a radio wave propagating through the ionosphere depends both on the frequency of the radio wave and the total electron content (TEC) between the transmitter and the receiver. TEC, a key parameter in describing ionospheric behavior, represents the total number of electrons present along the path from the satellite to the receiver, where 1 TEC equals 10^{16} electrons/m^2 [4]. At some frequencies the radio waves pass through the ionosphere. At other frequencies, the waves are reflected by the ionosphere. When propagating through Earth's ionosphere, radio waves interact with free electrons along the transmission paths, introducing group delay and phase advance [5]. Travel through this layer also impacts GPS signals, resulting in effects such as deflection in their path and delay in the arrival of the signal [6]. The ionospheric total electron content varies in response to Earth's space environment, interfering with Global Satellite Navigation System (GNSS) signals, resulting in one of the largest sources of error for position, navigation and timing services. Networks of high-quality ground-based GNSS stations provide maps of ionospheric total electron content to correct these errors, but large spatiotemporal gaps in data from these stations mean that these maps may contain errors [7].

Telecommunication between satellites and the ground applies high enough radio frequencies (RF) that permit the signal to pass through the ionosphere, while ground-to-ground communication makes use of reflection from the ionosphere. Thus, as ionospheric properties vary during space weather events, RF communication is also affected. Consequently, the signal can be distorted, fade or disappear totally, and the signal may propagate along unusual paths and to unexpected distances. Satellite navigation systems have many different applications that rely on ionospheric plasma references that vary in a wide range of temporal and spatial scales, causing determination of the influence on RF signals difficult [8].

Students will learn that the ionosphere constitutes a plasma medium revealing neutrals, ions, and electrons. While the ionospheric plasma density is typically an order of magnitude (or more) lower than the atmospheric neutral gas density, electrostatic charging can lead to the formation of plasma sheath and wake structures around an object that artificially increase its effective collecting area [9]. Figure 3 shows a TEC map used to estimate the GPS signal delay due to the ionospheric electron content between a receiver and a GPS satellite

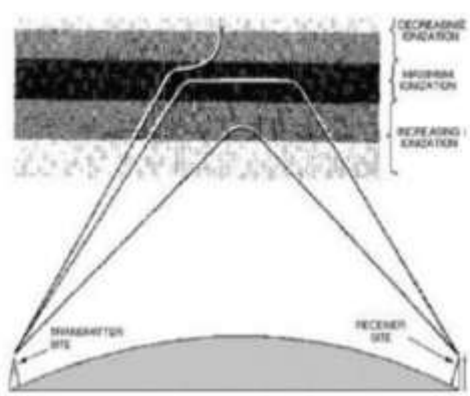

Figure 3. Effect of ionosphere density on radio wave propagation

Increased TEC and ionosphere irregularities caused by space weather can lead to ionospheric scintillation [10]. Severe scintillation circumstances make it difficult to determine a position and prohibit a GNSS receiver from grabbing onto the signal [11]. Less severe scintillation circumstances may cause positioning results to be less accurate and confident [12]. Figure 4 illustrates ionospheric impacts on GNSS.

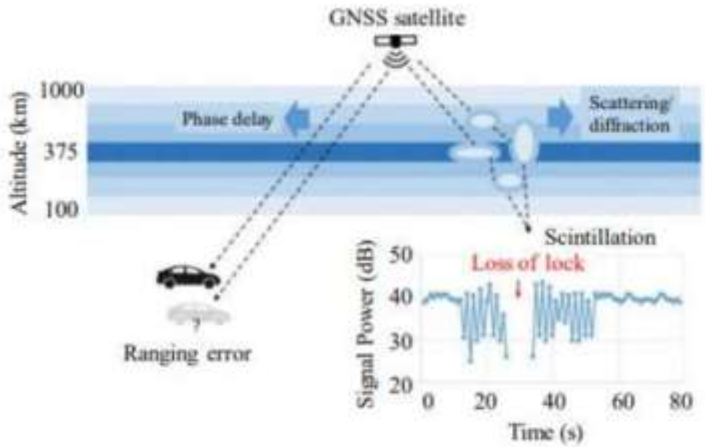

Figure 4. Ionospheric impacts on GNSS [13].

In the process of spacecraft reentry relying on shortwave propagation, ionospheric reflection is also required to achieve over-the-horizon communication, as illustrated in Figure 6. The speed of the reentry spacecraft may reach up to Ma = 10 or even higher. When the spacecraft quickly passes through the ionosphere of the large airspace, the high dynamic, time-varying, and nonstationary channel characteristics between the ground station and the spacecraft, and its communication link will be seriously affected. Most importantly, in addition to the influence of the high maneuver of the reentry spacecraft on the channel, the high dynamic propagation effect attached to the plasma sheath will complicate the establishment of the entire integrated channel. When the speed of a spacecraft reaches Ma = 20, the electron density reaches approximately 1020 cm^{-3}, and the plasma frequency approaches terahertz [14].

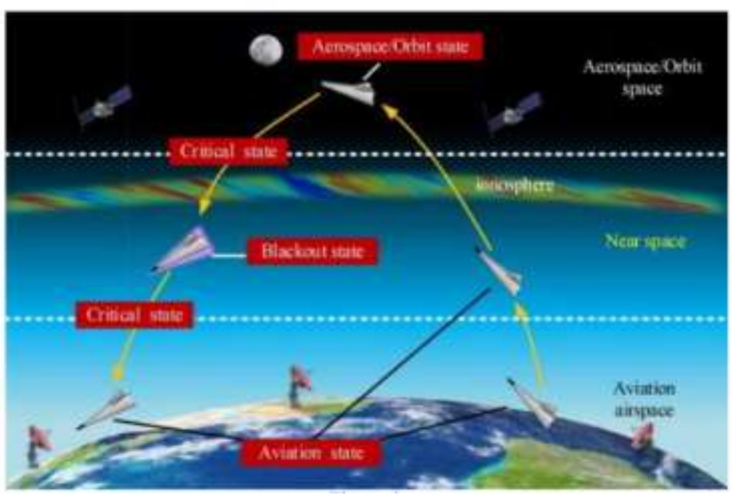

Figure 6. Spacecraft entry [15]

Plasma irregularities are an important subject for ionospheric studies, as they can cause disturbances of the trans-ionospheric radio wave signals. When propagating through Earth's ionosphere, the radio waves interact with free electrons along the transmission paths, introducing group delay and phase advance. When the radio waves strike a volume of plasma irregularities, rapid fluctuations of the carrier phase and amplitude are usually observed from ground-based receivers, which is also called ionospheric scintillations [16].

Plasma irregularities actively cause collection of a net positive ion current at one part of the spacecraft to be balanced by a net electron current at the other part. Subsequent disruptive radio wave propagations correlate with electron density, for which total electron count (TEC) measurements significantly indicate threshold levels that forecast NOAA's Warning Alerts for radio blackouts [17]. Propagation of radio waves is affected due to TEC, changes in plasma and electron densities, formation of ionospheric plasma sheath due to spacecraft reentry, and increased interaction of electrons, ions, molecules present in the atmosphere with radio waves. The total delay suffered by a radio wave propagating through the ionosphere depends both on the frequency of the radio wave and the TEC between the transmitter and the receiver [18]. At other frequencies, the waves are reflected by the ionosphere. TEC changes in plasma and electron densities, formation of ionospheric plasma sheath due to spacecraft reentry, increased interaction of electrons, ions, and molecules present in the atmosphere with radio waves, result in ionospheric scintillation [19]. Severe scintillation circumstances make it difficult to determine a position and prohibit a GNSS receiver from grabbing onto the signal [20]. Less severe scintillation circumstances may cause positioning results to be less accurate and confident [21].

Problem

NASA defines debris as "any man-made object in orbit around the Earth that no longer serves a useful purpose". Figure 3 illustrates the growth in the number of space debris over the past decades. Most of this debris eventually ends with an uncontrolled re-entry into the Earth's atmosphere. Currently 1-2 debris re-entries (on average) are recorded daily [22]. The majority are consumed by fire before reaching cruise flight levels, but 2-4% are big enough to reach the ground [23]. There are several such occurrences per year [24].

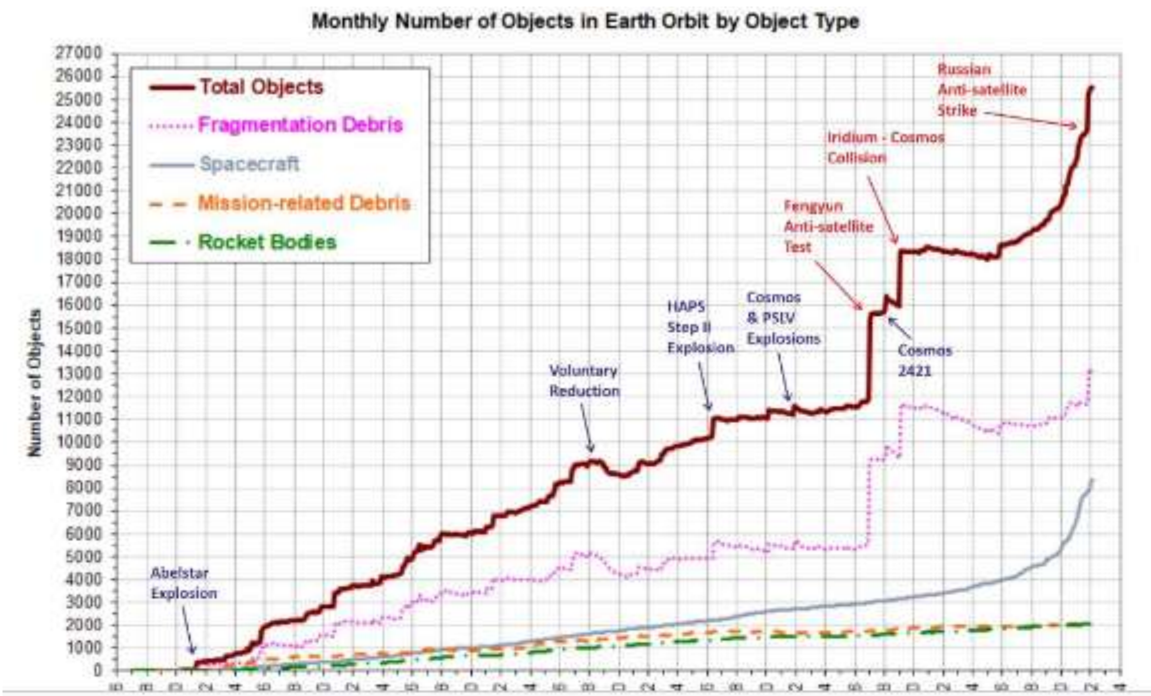

Figure 5. of the debris amount LEO >10 cm in size with annotations of main generating events [25].

As of March 2023, 299 Starlink V1 (first generation) satellites re-entered the Earth's ionosphere [26] at a mass of approximately 300 kg each. Since the beginning of the space industry, approximately 20,000 tons of material [27] have been demolished during reentry, meaning a similar amount may remain as plasma dust. The Starlink V2 satellite constellation (just one of many planned mega-constellations) intends to have 42,000 satellites, each the mass of a SUV, truck, or large car (1250+ kg). Each satellite has a planned lifetime of only 5 years (if successful and many satellites are failing sooner), Thus to maintain the mega-constellation, 23 satellites per day will complete a re-entry burn in the upper atmosphere. This is approximately 26,308 kilograms (29 tons) of satellite re-entry material every day, just for the Starlink mega-constellation [28]. The locations of re-entries are essentially randomly distributed; however, space launch regions likely have greater densities of plasma dust development. Increased ionization in these regions risk adverse impacts for launch success as ions interfere with electronics. Moreover, the layer of growing re-entry particulate does not dissipate when the satellite demolishes. It stays stagnant in the upper atmosphere/lower ionosphere for several years before decaying into the lower atmosphere in a best-case scenario.

Purpose
This paper examines how the air density of the upper atmosphere changed globally in response to space weather energy being deposited at high latitudes during the Starlink geomagnetic storms of February 2022 [29] and aims to explore approaches Subject Matter Experts deem appropriate for risk management of GPS/ GNSS inaccuracies.

Methods and Results

A literature survey was conducted to collect recommendations for improving GPS/ GNSS accuracy. Predicting associated geomagnetic activities in advance further required warning systems to be in place whenever TEC changes with plasma and electron densities, formation of ionospheric plasma sheath due to spacecraft reentry, increased interaction of electrons, ions, and molecules present in the atmosphere with radio waves, are observed [30]. Ionospheric changes in the path and velocity of radio waves significantly impact the accuracy of satellite navigation systems such as GPS/GNSS. Therefore, neglecting changes in the ionospheric TEC may introduce tens of meters of error in the position calculations [31]. When the speed of a spacecraft reaches Ma = 20, the electron density reaches approximately 1020 cm^{-3}. Space industry funding will enable more accurate chemical modeling of the atmosphere, ionosphere, and magnetosphere and the chemicals, debris, and materials being added. It is already suspected that the resulting re-entry alumina increases ozone depletion [32].

The ionosphere significantly affects GNSS positioning by causing signal delays and bending. To compensate for these effects, researchers have developed various mathematical models to describe ionospheric behavior. Some well-known models include the Klobuchar model, NeQuick model [33], BeiDou Global Ionospheric delay correction Model (BDGIM) [34], International Reference Ionosphere (IRI) model systems [35], and Global Ionosphere Map (GIM). Developed by the U.S. Department of Defense, the Klobuchar model is widely used in GPS systems content [36]. Global Ionosphere Maps (GIM) provide high temporal resolution (e.g., hourly updates), reflecting the ionosphere's current state, including short-term variations and disturbances like geomagnetic storms. They are ideal for real-time applications requiring current ionospheric information, such as precise GNSS positioning, satellite communication adjustments, and space weather monitoring [37]. The ionospheric total electron content varies in response to Earth's space environment, interfering with Global Satellite Navigation System (GNSS) signals, resulting in one of the largest sources of error for position, navigation and timing services. Networks of high-quality ground-based GNSS stations provide maps of ionospheric total electron content to correct these errors, but large spatiotemporal gaps in data from these stations mean that these maps may contain errors [38].

Discussion

Global Navigation Satellite Systems (GNSSs) have become an integral part of modern life, providing precise positioning and navigation capabilities for a wide range of military, civilian, and commercial applications. Since the launch of the first Global Positioning System (GPS) satellite in 1978 and the completion of the GPS network in 1993, other countries and regions have developed their own systems, including Russia's GLONASS, the European Union's Galileo, and China's BeiDou [39]. These systems have enabled numerous applications, from vehicle navigation and mobile phone positioning to autonomous vehicles [40]. However, GNSS accuracy is significantly affected by ionospheric delays, which remains a critical challenge in satellite positioning [41]. Recent studies have further highlighted these challenges, particularly in the context of precise positioning applications. Lyu et al. [42] investigated the uncertainties in interpolating satellite-specific slant ionospheric delays and their impacts on PPP-RTK, while Tang et al. [43] examined how equatorial plasma bubbles and associated ionospheric gradients affect GNSS PPP-RTK performance. The ionosphere, a layer of the Earth's upper atmosphere, contains free electrons that can alter the speed and direction of radio signals passing through it [44]. This delay varies with factors such as solar activity, geomagnetic activity, and atmospheric disturbances, leading to reduced positioning accuracy. In recent years, researchers have turned to deep learning methods to predict ionospheric Total Electron Content (TEC) and correct for navigation errors [45].

The space industry must fund more accurate chemical modeling of the atmosphere, ionosphere, and magnetosphere and the chemicals, debris, and materials they are adding to it. It is already suspected that the resulting re-entry alumina may increase ozone depletion [46]. Additionally, since space is not considered an earth environment, there is no regard for the sensitivity of the ionosphere, Van Allen Belts, plasmasphere, or magnetosphere. These plasma systems may indeed be more sensitive than suspected due to their low density.

As of March 2023, 299 Starlink V1 (first generation) satellites have already re-entered [47] at a mass of approximately 300 kg each. This amount of material is 500 million times the mass of the Van Allen Belts. In 2022 alone, the space industry polluted approximately 2 billion times the mass of Van Allen Belts (over 500 tons) in reentry particulate and material from all launches. Since the beginning of the space industry, approximately 20,000 tons of material [48] have been demolished during reentry, meaning a similar amount may remain as plasma dust. This amount is over 100 billion times greater than the Van Allen Belts. This re-entry material will be globally distributed since re-entries are globally distributed. The locations of re-entries are essentially randomly distributed. Space launch regions likely have greater densities of plasma dust development. This increase in ionization in these regions could have adverse impacts for launch success as ions can interfere with electronics. The layer of growing re-entry particulate does not dissipate when the satellite demolishes. It stays stagnant in the upper atmosphere/lower ionosphere for several years before decaying into the lower atmosphere in a best-case scenario. In a worst-case scenario, the particulate stays there indefinitely. Since this material is replenished every day, any potential natural decay to the ground may be negligible. It should be noted that rocket and satellite exhaust are also creating plasma dust [49]. If the metal dust is settling into the atmosphere after several years, the repercussions of vast amounts of metal dust in the atmosphere include dangers to the ozone [50], but any other potential impacts are unknown.

Conclusion

K-12 students will learn the Earth's atmosphere that they breathe is minimally represented but consists of layers of distinct composition and effects. The ionosphere is one such layer consisting of a distinct plasma medium revealing neutrals, ions, and electrons. While the ionospheric plasma density is typically an order of magnitude (or more) lower than the atmosphere students are familiar with, its characteristic neutral gas density, electrostatic charging leads to the formation of plasma sheath and wake structures around satellites as they descend from Lower Earth Orbit (LEO) on re-entry into Earth's atmosphere. Plasma and the formation of plasma sheath are important topics students will learn when they begin to study the Earth's Moon and early lunar operations of robotic landers and rovers. Global Positioning System (GPS)/ Global Satellite Navigation System (GNSS)communications students utilize rely on the accuracy of satellite transmission and reception of radio wave signals. SpaceX operations have been pivotal in GPS technology development and global coverage. With greater constellations of 300+ satellites being launched into LEO, their eventual demise and atmospheric re-entry entail plasma perturbations that will impact radio wave trajectories. This paper investigates how such perturbations affect radio waves and how they are monitored.

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