17th International Conference on Space Operations, Dubai, United Arab Emirates, 6 - 10 March 2023.
Copyright ©2023 by the Mohammed Bin Rashid Space Centre (MBRSC) on behalf of SpaceOps. All rights reserved. One or more authors of this work are employees of the government of USA, which may preclude the work from being subject to copyright in USA, in which event no copyright is asserted in that country

SpaceOps-2023, ID # 572

Space Weather Environment During the SpaceX Starlink Satellite Loss in February 2022

Tzu-Wei Fang[a*], Adam Kubaryk[a,b], David Goldstein[c], Zhuxiao Li[a,b], Tim Fuller-Rowell[a,b], George Millward[a,b], Howard J. Singer[a], Robert Steenburgh[a], Solomon Westerman[c], Erik Babcock[c]

[a] NOAA Space Weather Prediction Center, 325 Broadway, Boulder, CO 80305, USA, tzu-wei.fang@noaa.gov
[b] CIRES, University of Colorado at Boulder, 216 UCB, University of Colorado Boulder campus, Boulder, CO 80309, USA
[c] SpaceX Starlink, 1 Rocket Road, Hawthorne, CA 90250, USA
* Corresponding Author

Abstract

SpaceX Starlink launched and subsequently lost 38 of 49 satellites due to enhanced neutral density associated with a geomagnetic storm on 3 February 2022. Fang et al. [1] examines the space weather conditions related to the satellite loss, based on observations, forecasts, and numerical simulations from the National Oceanic and Atmospheric Administration (NOAA) Space Weather Prediction Center (SWPC). Working closely with the Starlink team, the thermospheric densities along the satellite orbits were estimated and the neutral density increase leading to the satellite loss was investigated. Simulation results suggest that the NRLMSIS-00 neutral density estimates used by the Starlink team in pre-launch Monte Carlo analysis tended to underestimate the neutral density compared to predictions from the operational WAM-IPE physics-based model during the geomagnetic storm. The numerical simulation indicated this minor to moderate geomagnetic storm was sufficient to create 50% to 125% density enhancement at altitudes ranging between 200 km and 400 km. With the increasing solar activity of Solar Cycle 25, satellites in low-Earth orbit (LEO) are expected to experience an increasing number of thermospheric expansion events. In this presentation, space weather information from the Feb 2022 event will be discussed in detail. The outcomes through continuous engagement between NOAA SWPC and the SpaceX Starlink team will also be shared.

Keywords: Space Weather, Satellite Drag, Neutral Density

1. Introduction

SpaceX Starlink lost 38 of 49 satellites after the launch of Group 4-7 in Feb 2022 due to enhanced neutral density associated with a geomagnetic storm. Based on observations, forecasts, and numerical simulations from the National Oceanic and Atmospheric Administration (NOAA) Space Weather Prediction Center (SWPC), the study by Fang et al. [1] provided a detailed analysis of the space weather conditions and neutral density environment during the event. NOAAs SWPC is the official source for space weather forecasts, watches, warnings and alerts in the US. SWPC's scientists are working to improve the Nation's preparedness for space weather events like solar storms and flares by improving the accuracy and timeliness of space weather forecasts, and establishing procedures for responding to and recovering from space weather events. With an increasing number of satellites in LEO orbits, it becomes crucial for SWPC to establish suitable alerts and warnings based on neutral density predictions to provide users guidance for preventing satellite losses due to drag and to aid in collision avoidance calculations. In this study, SWPC's model simulation are used to compare with Starlink data and operational analysis during the event. The findings and current engagement on improving neutral density environment will also be shared in this presentation.

2. Space Weather Conditions

A series of Coronal Mass Ejection (CMEs) erupted on the Sun starting from 29th January 2022, propagated towards Earth, and were subsequently observed by the Solar and Heliospheric Observatory (SOHO) spacecraft at the L1 point (1st Lagrange point). The solar wind plasma travelled from the Sun with an elevated speed of around 500 km per second toward the Earth. With the estimated solar wind speed and simulations from numerical models, forecasters at the SWPC predicted that the fast speed solar wind would hit Earth within 3 to 4 days. A few days later, on February 3rd, the CMEs arrived at Earth with the strong southward interplanetary magnetic field (IMF Bz) producing a geomagnetic storm in the near-Earth environment, including perturbations in the thermosphere and ionosphere. Based on various observations in space and on the ground, the CME event enhanced the global geomagnetic activity Kp index (for geomantic activity) to a value of 5, and the enhancement lasted for six hours on

Copyright ©2023 by the Mohammed Bin Rashid Space Centre (MBRSC) on behalf of SpaceOps. All rights reserved. One or more authors of this work are employees of the government of USA, which may preclude the work from being subject to copyright in USA, in which event no copyright is asserted in that country

both 3 and 4 February. Based on the Kp values, the event was classified as a minor storm according to SWPC's Space Weather Scales (https://www.swpc.noaa.gov/noaa-scales-explanation).

There have been many SpaceX launches that were dedicated to deploy the Starlink system since 2009. Figure 1 illustrates the 2-day integrated 3-hour Kp index (launch day and the day after) and daily F10.7 (solar radio flux at 10.7 cm, 2800 MHz) from prior launches with satellite perigees below 275 km. Several launches occurred after the event in February 2022, but all of the launches targeted perigees were changed to above 300 km till June 2022. Increased F10.7 indicates higher solar UV forcing with more energy absorbed in the upper atmosphere. The geomagnetic activity Kp index is used to specify forcing by the high-latitude convection electric field resulting from the interactions between the solar wind and Earth's magnetic field that leads to Joule heating in the ionosphere and thermosphere. A high Kp index is also an indicator of extra auroral particle precipitation heating into the ionosphere and thermosphere. As shown in Figure 1, compared to prior events with perigees less than 275 km, the F10.7 and 2-day integrated Kp are significantly higher for the 3rd February launch.

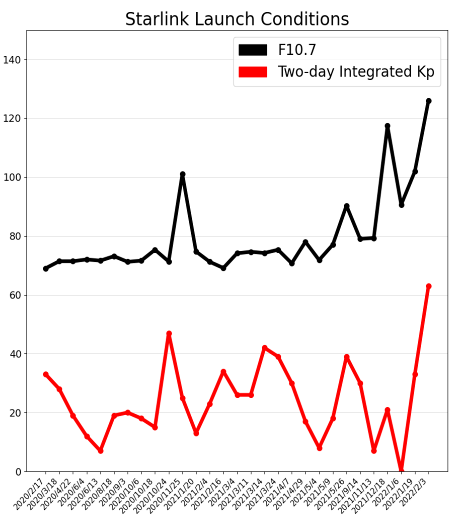

Figure 1. F10.7 and two-day integrated Kp for all SpaceX Starlink launches that went into an orbit with perigees lower than 275 km.

In study carried out by Fang et al. [1], the operational WAM-IPE model outputs were analysed for the event. WAM-IPE provides neutral atmospheric parameters from the ground to the upper thermosphere at around 500 km depending on the solar activity levels. WAM was developed based on the spectral version of the National Centers for Environmental Prediction (NCEP) Global Forecast System (GFS) used for medium-range numerical weather prediction. The WAM system is used to quantify the impact of lower atmosphere weather on the upper atmosphere and ionosphere, as well as the response to solar and geomagnetic activity. The thermospheric parameters calculated by WAM are fed into IPE for calculating the responses in the ionosphere. IPE is a time-dependent and global three-dimensional model that provides densities, temperatures, and velocity of ions and electron from 90 km to several Earth radii. In the current concept of operation (CONOPS), WAM-IPE is run four times daily, providing two-day forecasts. Observed solar wind parameters are used whenever observational values are available. Lower atmospheric data assimilation in only carried out twice daily to maintain stability of the coupled model. As the mode integrates through periods without observed space weather drivers, the forecast 3-hour Kp and daily F10.7 issued by SWFO are ingested into the model, and used to estimate solar wind parameters. In this study, WAM-IPE's operational outputs are used to analyze the neutral atmosphere environment that Starlink satellites experienced and to estimate the geomagnetic storm impact on the neutral density variability.

3. Model Results and Observations

The differences in neutral density results between WAM-IPE and empirical MSIS model provide some estimation of possible differences in satellite drag that the Starlink team had not anticipated. In these simulations, the WAM-IPE was driven exclusively by the daily F10.7 and one-minute cadence solar wind and interplanetary magnetic field parameters, while MSIS was driven by daily F10.7 and Ap values converted from the observed or forecast 3-hour Kp. In WAM-IPE, the neutral density is calculated by summing the mass densities of atomic oxygen (O), molecular oxygen (O_2), and molecular nitrogen (N_2) at fixed altitudes. Both WAM-IPE and MSIS outputs are at ten-minute cadence. Comparisons of global mean density (not shown here) suggests that the WAM neutral density was consistently higher than MSIS throughout 3 and 4 February at all altitudes. The WAM density also displays significantly more small-scale perturbations and structure than MSIS. The small-scale spatial variability and structure shown in WAM density are associated with the realistic atmospheric weather patterns in the lower atmosphere that are expected in all our simulations, and the time-dependence in the response and recovery to energy injection enabled by the physical model. Therefore, the variability predicted by WAM for the event likely provides a much more realistic environment compared to those shown in MSIS. Empirical models driven by the 3-hour Kp or Ap may predict mean levels, but tend to be smooth due to the numerical fitting. The physics-based model, on the other hand, clearly depicts structure induced by waves from the lower atmosphere and structure induced by the time

17th International Conference on Space Operations, Dubai, United Arab Emirates, 6 - 10 March 2023.
Copyright ©2023 by the Mohammed Bin Rashid Space Centre (MBRSC) on behalf of SpaceOps. All rights reserved. One or more authors of this work are employees of the government of USA, which may preclude the work from being subject to copyright in USA, in which event no copyright is asserted in that country

dependence of the solar/magnetospheric drivers used to drive the model. This variability could add a 30 - 50% variation in density locally. The impact of this structure and variability on satellite orbit projections needs to be further investigated.

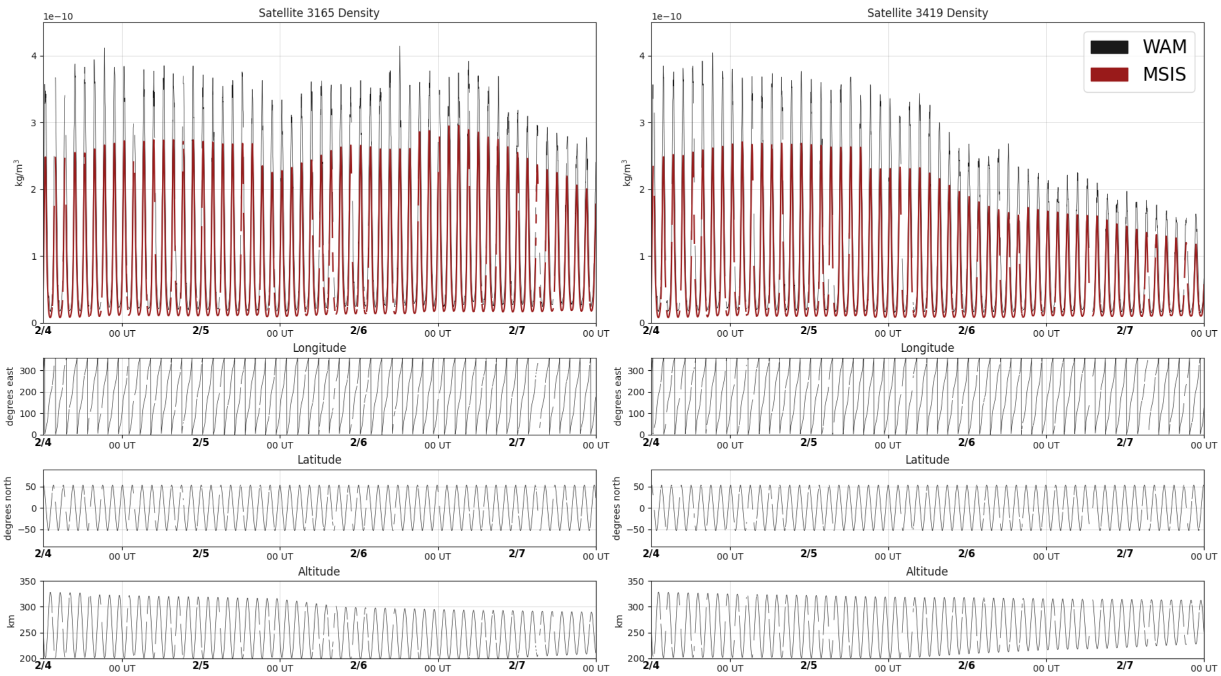

Figure 2. Neutral density sampled along orbits of two Starlink satellites (3165 and 3419) from WAM-IPE (black) and MSIS (brown) global densities. The locations for these satellites in longitude, latitude, and altitude are also included.

The detailed orbit information for all satellites from this launch and prior launches were provided by the Starlink team. Figure 2 shows the orbits of two satellites (#3165 and #3419) that were launched along with the other 49 satellites on 3 February and did survive the higher neutral density environment associated with the geomagnetic storm. Minor data gaps can be seen in the figure. Even though all the Starlink satellites were deployed together the onboard orbit determination estimates showed different altitudes for these two satellites. For satellite #3165, due to significantly increased drag and instability on orbit, the thrust applied for orbit raising was not initiated until 7 February. Thus, within the 5-day period, the perigee of the satellite remained low (~200 km) and only started to increase to a slightly higher altitude toward the end of the 5th day. The apogee also reduced from ~330 km to less than 300 km. On the other hand, the orbit raising process for satellite #3419 was able to start from early in the UT hours on 6 February. Based on the altitudes in this plot, the perigees also showed smooth increases as orbit-raising thrust was applied. Using the provided longitudes, latitudes, and altitudes for these satellites, the neutral density obtained from WAM and MSIS are sampled along the orbits. The unstable periods at the beginning of the orbits before 12UT on 4 February are omitted in the plot. Since all the satellites were released together and stayed in close to proximity, for an initial period the density results are very similar on 4 and 5 February for all 11 satellites that survived. With the faster orbit raising leading to increased perigee altitudes and calmer space weather conditions after 5 February, significant density decreases at perigees can be seen for satellite #3419. Overall, during the period, WAM densities are roughly 40-80% higher at perigees and 60-100% higher at apogees compared to those from MSIS. Based on further analysis carried out by the Starlink team, the at least 50% higher neutral density WAM suggested is approximately what was required to initiate safe hold for Starlink satellites. The Starlink team has implemented several system upgrades to ensure future low insertion missions can accommodate the satellite drag with increased solar and geomagnetic activities in solar cycle 25.

To estimate the reliability of WAM neutral density results, simulations are further compared with the onboard drag estimates obtained from Starlink satellite. The satellite telemetry data provides not only the satellite locations and satellite conditions, but also the satellite attitude, drag coefficient and drag acceleration estimated by the onboard

Copyright ©2023 by the Mohammed Bin Rashid Space Centre (MBRSC) on behalf of SpaceOps. All rights reserved. One or more authors of this work are employees of the government of USA, which may preclude the work from being subject to copyright in USA, in which event no copyright is asserted in that country

orbit determination algorithm based on a Kalman filter. Satellite drag varies strongly as a function of the neutral thermospheric density and the satellite ballistic coefficient. The comparisons of WAM density and estimated density from Starlink satellites at satellite perigees of each orbit of the eleven surviving satellites show that variations of WAM density with height agree well with changes in Starlink satellites observations. The decreased WAM neutral density with increased perigee altitudes follows the slope of the satellite observations. Comparing to the Kalman filter results, WAM density appears to have more variability throughout the period for all satellites. To better understand these differences, in the future it is necessary to carefully estimate neutral density along the orbit. More details based on this study will be presented in this talk.

4. Conclusions

For this space weather event, a series of Earth-directed and partially Earth-directed CMEs were detected by multiple spacecraft and ground-based observations between 29-31 January 2022. The CMEs were not particularly strong and SWPC forecast the CMEs to arrive at Earth as early as 2 February 2022. During this event, the CME arrival generated geomagnetic storms with Kp 5 for more than 6 hours on both 3 and 4 February. Even though this is considered a minor to moderate geomagnetic storm, the external energy injection into the thermosphere still caused thermospheric expansion that significantly enhanced the neutral density in the VLEO environment. SWPC had several watch, warning, and alert products in effect for this event beginning 31 January and continuing through 5 February. While this information provides useful and actionable guidance, improvement of the forecast skill on CME arrival time and better estimation of the CME impact on Earth's upper atmosphere still require significant research efforts to achieve the accuracy, along with confidence levels, that is urgently needed.

The WAM-IPE is SWPC's newest operational space weather model that captured the enhanced neutral density globally in early February 2022. Based on WAM-IPE simulations, the neutral density enhancement for this event was about 50% to 125%, depending on location and altitude during the event. The magnitude of the density increase is very common for a minor to a moderate geomagnetic storm. Thus, with increasing solar activity in the current solar cycle 25, the occurrence frequency of neutral density enhancement events of a similar magnitude will be very high. This geomagnetic storm event highlighted the need for the satellite industry to utilize improved models for specifying the response of the satellite environment to space weather and to incorporate this information into satellite design and operations. The study also demonstrated that the neutral density estimated by WAM-IPE at 210 km is significantly higher than that predicted by the NRLMSIS-00 model, leading to a level of satellite drag that was not anticipated by the Starlink team. Developing computational efficient data-assimilation techniques to utilize the large volume of on-orbit neutral density observations along with an operational model will allow SWPC to improve neutral atmosphere nowcasts. The current WAM-IPE forecasts are driven by F10.7 and Kp forecasts, which in turn rely on better predictions of solar activity and the solar wind impacting the Geospace environment. Commercial satellite operators receive general forecasts, watch, warnings, and alerts through NOAA's data and web services, but none are currently specifically focused on satellite drag at LEO. Thus, it is critical for SWPC to establish alerts and warnings for thermospheric density enhancement conditions. SWPC will continue to work closely with the Starlink team, and others in the spacecraft industry, to expand the current space weather services to provide neutral density alerts and warnings for satellite operators.

References

[1] Fang, T.-W., Kubaryk, A., Goldstein, D., Li, Z., Fuller-Rowell, T., Millward, G., et al. (2022). Space weather environment during the SpaceX Starlink satellite loss in February 2022. *Space Weather*, 20, e2022SW003193. https://doi.org/10.1029/2022SW003193