Space Weather

COMMENTARY
10.1029/2019SW002373

Key Points:

- Space weather is the main source of uncertainty in the position of objects in Low Earth Orbit (LEO) due to its impact on atmospheric drag.
- LEO is increasingly crowded with active satellites and debris; many thousands of additional satellites are planned for the near future.
- Researchers and policy makers must advance our ability to predict and manage the growing satellite and debris environment in LEO.

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Citation:
Berger, T. E., Holzinger, M. J., Sutton, E. K., & Thayer, J. P. (2020). Flying through uncertainty. Space Weather, 18, e2019SW002373. https://doi.org/10.1029/2019SW002373

Received 7 OCT 2019
Accepted 21 DEC 2019
Accepted article online 3 JAN 2020

Flying Through Uncertainty

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Abstract Space weather is the main source of uncertainty in the position of all objects in low Earth orbit (LEO) below about 1,000 km. The main impact is strong variation in the neutral density of the thermosphere as it responds to radiative inputs from the Sun in the extreme ultraviolet wavelength range, energetic particle precipitation in the high-latitude auroral zones, and global-scale electrical currents generated during geomagnetic storms. Waves and instabilities from the lower atmosphere can also influence thermospheric density in complex ways. The variation in neutral density leads to variable drag forces on satellites flying through the thermosphere, which in turn causes orbital track changes. We currently lack the ability to accurately model and predict the neutral density changes in the thermosphere in response to space weather inputs. Operational empirical models of thermospheric density are inaccurate during space weather events, and mandate that LEO orbital tracks carry large “error ellipsoids” around all objects to account for positional uncertainty. This leads to many more “conjunction” warnings than necessary as large error ellipsoids are frequently calculated to intersect in orbit. As the LEO domain becomes more crowded with the advent of commercial “megaconstellations” we face a growing challenge to reduce orbital uncertainties by developing whole atmosphere models to enable timely and accurate forecasts of thermospheric conditions. We recommend that researchers, forecasters, and policy makers coordinate to ensure that space weather research and forecasting is tightly integrated into upcoming changes to the operational Space Traffic Management system.

1. Introduction

On 2 September 2019 the European Space Agency (ESA) announced that it had raised the orbit of its Aeolus satellite to avoid a collision with the Starlink44 satellite (https://www.esa.int/Safety_Security/ESA-spacecraft-dodges_large_constellation), one of the current 120 satellites in SpaceX Corporation’s planned constellation of over 4,000 satellites for global internet connectivity. The orbital “conjunction” took place at approximately 318 km above sea level in low Earth orbit (LEO) with an estimated minimum distance of less than a kilometer at time of closest approach, with a greater than 1 in 1,000 chance that the satellites would actually collide. The operative words here are “approximately,” “estimated,” and “chance”—in fact, the satellite operators did not know exactly where their satellites were during the time leading up to the conjunction, with the degree of uncertainty measured in kilometers. To many this may sound strange—how can meter-sized objects that are easily tracked by radar and are orbiting in the “vacuum of space” according to the well-known laws of orbital mechanics have locations that are uncertain to levels of thousands of meters?

The answer is that all objects located between about 100 and 1,000 km above sea level, whether operational satellites or pieces of orbital debris, are flying through the upper atmosphere of the Earth. Specifically, this region of the atmosphere consists of the thermosphere and exosphere and is where space weather greatly disturbs the gas density on time scales of minutes to hours. Radiative inputs primarily from solar extreme ultraviolet (EUV) photons, direct heating via energetic particle precipitation in the auroral zones, and Joule heating from electrical currents generated as the highly variable solar wind buffets the Earth’s magnetosphere heat the thermosphere to varying degrees, causing it to expand upward with resultant increases in density at a given altitude. During quiet space weather conditions, the primary heating is from EUV radiation which can vary as evolving solar active regions rotate across the solar disk. During moderate to strong geomagnetic storms typically caused by solar wind high-speed streams (HSS), corotating interaction regions, or weaker coronal mass ejections (CMEs), Joule heating can increase to match radiative heating, causing much larger perturbations to thermospheric neutral density. And during severe to extreme geomagnetic storms caused by strong CMEs with...
significant periods of southward interplanetary magnetic field, Joule heating becomes the dominant input to the system, persisting over multiple-day periods in many cases (Knipp et al., 2004). Adding complexity to the problem, the thermosphere can also experience rapid and spatially variable “overcooling” and contraction during some events, due primarily to infrared radiation to space from CO₂ and NO molecules formed via chemical reactions in the storm time atmosphere (Knipp et al., 2017; Lei et al., 2012; Mlynczak et al., 2018). There is also energy and momentum transport from the lower atmosphere via flows and gravity waves (e.g., Jackson et al., 2019) that further complicate accurate modeling of space weather effects on thermospheric neutral density. Objects in LEO experience this spatiotemporal variation in density as changes in the drag force opposing their forward orbital motion, leading to changes (and hence uncertainty) in both the position along the established orbit at a given altitude (so-called “in-track” orbital changes) and orbital altitude.

2. Tracking and Managing Objects in LEO and the Impact of Space Weather

All objects larger than about 10 cm in orbit around the Earth (live satellites, dead satellites, rocket bodies, pieces of debris, etc.) are tracked by the U.S. Air Force (USAF) radar Space Surveillance Network (SSN) to establish the current “catalog” of Resident Space Objects (RSOs; Peterson et al., 2018). Position and velocity (i.e., state) uncertainty of orbital tracks are quantified by the “error ellipsoid” that virtually surrounds all objects in the catalog, representing the volume in space where an object is most likely to be at any given time (Bussy-Virat et al., 2018). Objects in LEO carry particularly large and variable error ellipsoids due primarily to the rapid density changes caused by space weather. Not all uncertainty in LEO is due to space weather: Thermal reradiation, attitude- and shape-dependent perturbations, and solar radiation pressure also contribute. But because we lack both full understanding of, and the ability to reliably predict, the dynamic density of the upper atmosphere, space weather is by far the largest source of uncertainty in LEO.

When error ellipsoids around two catalog objects are calculated to intersect at some point in their orbits, the USAF 18th Space Control Squadron (SPCS) in Colorado Springs, Colorado, issues a “Conjunction Data Message” (CDM) with information on the projected intersection of tracks, including an estimated probability of collision (Pc), to the relevant operators who must then decide what action, if any, they will take (Hejduk & Snow, 2018). A Pc value greater than 1 in 10,000 for LEO objects usually results in consideration of maneuvering (if possible) to change at least one of the orbital tracks. This seemingly conservative threshold for action is driven in part by the larger state uncertainty for LEO objects. For example, in the days leading up to the Aeolus-Starlink conjunction, both G2- and G3-level geomagnetic storms (https://www.swpc.noaa.gov/noaa-scales-explanation) occurred, further increasing uncertainties and possibly biasing the decision of ESA operators toward maneuvering their satellite to reduce the collision risk.

Orbital track changes due to density variations are altitude and spacecraft size, shape, and orientation dependent. For example, Figure 1 simulates in-track orbital errors for 2,653 cataloged satellites with perigees between 200 and 650 km for a moderate geomagnetic storm (Kp = 6—, i.e., a G2 storm matching the intensity of the storm preceding the Aeolus-Starlink conjunction) period compared to a quiet geomagnetic period (Kp = 1) as a function of perigee altitude, using the MSISE00 atmospheric model (Picone et al., 2002). The symbol colors encode the apogee altitude in kilometers, while the symbol sizes encode the scaled B* parameter, a fitting coefficient cataloged with orbital data that estimates Cd A ρ/2m where Cd is the assumed drag coefficient, A is an average frontal area in the ram direction, ρ is a reference atmospheric density, and m is the mass of the satellite. B* thus essentially represents how susceptible an orbital object is to drag forces. The trend of increasing error with decreasing altitude is clear, but in addition, as B* increases, that is, as the object’s sensitivity to drag forces increases, the error at any given altitude increases. Figure 1a shows that the in-track orbital position errors during a 3-hr duration G2 geomagnetic storm can range up to 2 km larger than 3-hr quiet period values. For the typical perigee altitudes planned for upcoming large communication constellations (500–600 km), the errors range up to values of 500–700 m. However, for a storm duration of 18 hr, which is possible for moderate to strong geomagnetic storms, Figure 1b shows that the cumulative in-track errors at altitudes below 550 km can increase up to 14 km or more, depending on the scaled satellite B* value. At 550-km perigee altitude, the errors can range up to 7 km. A position error on the order of 10 km is huge compared to the accuracy of the last established position which has a nominal precision measured in
meters for S-band radars. Note, however, that even the tracking precision is susceptible to space weather since disturbed ionospheric conditions during geomagnetic storming can significantly degrade our ability to estimate the group velocity of radar signals and hence lead to lower precision in the location of orbital objects (see, e.g., Hapgood, 2010).

For the largest space weather events caused by CMEs with sustained southward magnetic fields, these numbers scale nonlinearly to values that can quickly move objects so far from their last-established tracks that the LEO catalog becomes useless for conjunction analysis and must be reestablished by the SSN. For example, in the last extreme geomagnetic storm on record, the great Halloween Storm of 2003, anecdotal testimony from USAF operators during the storm recounts that the majority of LEO satellites were temporarily lost, requiring several days of around-the-clock work to reestablish the catalog.

Fortunately, the Halloween storm did not cause any major collisions that we know of. But if a geomagnetic storm on the level of the 2003 event were to occur today, the situation could be very different. Most satellite operators today have never experienced anything like the Halloween 2003 storm, and there are now over 1,700 operational satellites and at least 19,400 pieces of debris larger than 10 cm in LEO (Liou, 2018; NASA ODPO, 2019). With kilometer-scale error ellipses around every RSO, the 18th SPCS is now issuing up to 35,000 CDMs per day (https://spacenews.com/data-sharing-seen-as-critical-to-future-of-space-situational-awareness). This number will only increase with the launch of so-called “megaconstellations” to LEO over the coming years (Radtke et al., 2017). The large majority of CDMs have Pc values below action thresholds, but the number above threshold, like the Aeolus-Starlink conjunction, will increase steadily as the LEO population density increases. A future extreme geomagnetic storm will move all objects in LEO to new, temporarily unknown, orbits and will present an even greater challenge to satellite operators and SSN catalog maintainers.

3. Future Directions in Space Traffic Management

Recognizing both the commercial opportunities and the challenges that the rapid growth of LEO satellites pose, in 2018 the White House issued Space Policy Directive 3 (https://www.whitehouse.gov/presidential-
actions-space-policy-directive-3-national-space-traffic-management-policy/), which instructs the Department of Defense to transition responsibility for civilian satellite conjunction warning to the Department of Commerce (DOC). In response, the DOC Office of Space Commerce and the National Institute for Standards and Technology recently held a workshop in Boulder, Colorado, to identify the technical challenges inherent in assuming this responsibility (https://www.nist.gov/news-events/events/2019/09/space-commerce-workshop). The meeting emphasized that with several megaconstellations already approved and deploying, current technologies for tracking satellites, predicting conjunctions, and analyzing courses of action to avoid collisions will need to be improved, and fast. In addition, the workshop identified a need to better coordinate the elements of Space Domain Awareness (SDA) – identifying, tracking, and predicting the behavior of RSOs in a given space domain; Space Traffic Management (STM)– analyzing orbits and coordinating conjunction avoidance maneuvers; and Space Weather forecasting– predicting the environmental conditions in space and providing accurate, reliable, and timely data to STM models. Presently, these functions are somewhat disjoint in the United States, while the ESA coordinates space weather research and forecasting and SDA within its new Space Safety Programme. This variable organizational landscape, both within and across national boundaries, is an additional source of uncertainty for satellite and constellation operators and will require advances in space law to clarify international roles and responsibilities and coordination mechanisms.

Space weather was the focus of an afternoon panel of the DOC workshop, with particular emphasis on upgrading the technology currently used to characterize and predict the LEO space environment, particularly thermospheric density. Current empirical models of the thermosphere predict densities fairly well in benign solar wind regimes but fail badly during geomagnetic storms—precisely when analysts need good information the most. Jackson et al. (2019) review the current capabilities of “whole atmosphere” models to accurately predict space weather impacts on the upper atmosphere. They present a useful roadmap that will lead to advanced nonhydrostatic, data assimilative, models of thermospheric neutral density and ionospheric impacts that will enable reliable forecasting of oncoming geomagnetic storm effects, better understanding of tracking radar ionospheric perturbations, and ultimately a reduction in error ellipsoid radii with a concomitant decrease in the number of required CDMs. Related to this, there is a need for real-time precise orbit determination data from GPS-equipped satellites along with data release policies for public satellites and commercial data markets for private satellites. These data will greatly increase the amount of information available for calibration and assimilation into the full-physics forecasting models. There is also a pressing need for new models of vehicle gas dynamic and radiative interactions that will enable more accurate calculations of the non-Keplerian forces on RSOs. Lastly, the workshop identified the need for increased research into artificial intelligence systems that can rapidly analyze complex orbital environments, tracking data, and maneuver schedules to determine more accurate probabilities of collision, and advise operators or autonomous satellite systems of best actions.

4. Recommendations

It was pointed out during the DOC workshop that SpaceX is already executing autonomous maneuvers within their Starlink constellation. Are we sufficiently prepared for a future with hundreds or perhaps thousands of satellites simultaneously moving themselves to new orbits? Current levels of research funding and policy debate indicate that we may not be. Without significant improvements in, and coordination of, SDA, STM, and space weather forecasting technology there is a real risk that we will reach exponentially increasing levels of cascading collisions that could render the LEO domain unusable for decades or possibly centuries (Kessler et al., 2010) with devastating consequences for weather forecasting, space-based intelligence, and space commerce. The research and commercial STM communities must increase their efforts to produce the models, analysis and decision tools, and visualizations that satellite operators need, while policy leaders work to provide clarity on how the SDA/STM and space weather communities can better work together to decrease the uncertainties inherent in LEO operations. Space weather effects in orbit are not all bad: Higher solar and geomagnetic activity levels drag space debris down into reentry orbits, gradually cleaning up the LEO environment. But the weak activity levels of Solar Cycle 24 were not particularly helpful in this regard and may have also resulted in a cohort of satellite operators and regulators who are unaware of the impact that the next extreme geomagnetic storm will have on an increasingly congested LEO environment.
Acknowledgments
The authors thank Tim Fuller-Rowell, Matt Hejduk, David Jackson, Moriba Jah, Delores Knipp, Martin Mlynczak, and Kent Tobiska for enlightening discussions that contributed to the genesis of this Commentary. T. E. B., E. K. S., and J. P. T. acknowledge the generous support of the University of Colorado Chancellor’s Office Grand Challenge Initiative “Our Space. Our Future” in funding this effort via the Space Weather Technology, Research, and Education Center. M. J. H. was funded for this effort by the University of Colorado Department of Aerospace Engineering Sciences. We thank the Department of Commerce for hosting the Space Commerce Workshop on their Boulder, Colorado, campus. The data used to create Figure 1 are available at scholar.colorado.edu for download under a Creative Commons Attribution-Noncommercial-Share Alike 4.0 License. The title of the data set is “orbital error as a function of geomagnetic conditions” and can be accessed online (https://doi.org/10.25810/c3x1-jw11).

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