Proceedings of the Annual General Donald R. Keith Memorial Conference
West Point, New York, USA
May 2, 2024
A Regional Conference of the Society for Industrial and Systems Engineering

Analysis of Navigation Solution Parameters Affected by High-Latitude Ionospheric Scintillation

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Author Note: We, the authors, would like to express gratitude to our project advisors, COL Diana Loucks, Dr. Carolann Koleci, and Dr. Jason Derr. We are infinitely appreciative of your expertise and mentorship. This work was supported by NSF IAA-2144942; SAGA network is operated by Illinois Institute of Technology under NSF AGS-1651465, data is publicly available at http://apollo.tbc.iit.edu/~spaceweather/live/?q=SAGA. Technical expertise provided by Dr. Anthea Coster and Dr. Seebany Datta-Barua. The views expressed herein are those of the authors and do not reflect the position of the United States Military Academy, the Department of the Army, or the Department of Defense.

Abstract: A higher likelihood of geomagnetic storm activity combined with a limited number of satellites in view of high latitude receivers poses great challenge in navigating high-latitude regions during periods of solar maximum. Using data from high-resolution Connected Autonomous Space Environment Sensor (CASES) GPS receivers located in Poker Flat Research Range (PFRR), Alaska, we can analyze the effect that the rate of total electron content change (ROT) has on deviations in position navigation solutions through regression models. The data comes from a geomagnetic storm that occurred on August 26, 2018, allowing the results to resemble those that could occur in the solar maximum. The results show that internal algorithms in high quality GPS receivers correct position solutions and mitigate the effects of space weather.

1. Introduction

The current Global Positioning System (GPS) constellation is comprised of satellites in medium earth orbit, which excludes polar orbit (National Coordination Office for Space-Based Positioning, Navigation, and Timing, 2022). This exclusion assumes that there is not a substantial justification to put GPS satellites in a polar orbit. Certain stakeholders, such as Arctic GPS-users, inherently deal with the issue of geometric dilution of precision (GDOP) because there is one large sector of the sky that never contains GPS satellites. Historically, having satellites orbit over both poles would only benefit a small customer-base, but as the access to the Arctic becomes much more viable for both military and commercial entities, this assumption is being dismantled. Much GPS-based research on the ionosphere is primarily conducted in areas where most GPS users live—below the Arctic. Therefore, much of the GPS issues that are solely specific to the Arctic go largely unmitigated (McGranaghan et. al., 2018). The northern lights, or aurora borealis, is as much of a beautiful spectacle to us as it is a problem for low-grade GPS receivers, and with the upcoming solar maximum, an increase in the number of geomagnetic storms and substorms is expected.

Our research aims to better understand the operational impacts that space weather events have on GPS systems in the Arctic region (66.5 degrees north or greater). The elements of our research system include arctic personnel, GPS satellites, unencrypted GPS receivers, and space weather. The impacts are examined by measuring variation in GPS position solutions caused by the scintillation activity that results from space weather events. Ionospheric scintillation is the rapid fluctuation in radio signals, including GPS L1, caused by small scale structures in the ionosphere (Space Weather Prediction Center, n.d.). The data from PFRR is collected at a high latitude and during a geomagnetic storm; conditions that cause increased deviation in position navigation solutions in a GPS receiver. The analysis of this study is limited to directionless deviation in position navigation solution because the GPS system is extremely vast and there are dozens of factors that could contribute to offset in a particular direction. Because of uncertainties due to those variables, an operational index is most user-friendly when it shows a range of deviation based on ionospheric conditions measured by the GPS. Several variables needed to be accounted for to provide a system free of bias, namely atmospheric delays and receiver biases. Our system attempts to mitigate the effects of tropospheric, multipath, relative, or noise error on GPS systems. To isolate the effects of scintillation, we calibrated our system by running a model void of external precision-harming processes and tropospheric delays through deliberate Skydel simulation software configuration. The main efforts of our work were focused on removing the receiver biases, calculating pseudorange offsets that run the simulation, and correlating the data to the visible discrete aurora.

2. Methodology

2.1 Receiver Bias Correction

CASES receivers record observations of GPS signals and calculate estimates of slant total electron content (TEC) based on the differences derived from dual-frequency observations. TEC is a measurement of the number of electrons between the receiver and the satellite in a meter diameter space (Misra & Enge, 2006). The Space Weather Lab at Illinois Technical Institute provided us a raw form of the data that is inherently biased due to the nature of receiver hardware (Space Weather Lab at IIT, 2023). Each receiver is built differently and interprets TEC with its own bias that is also dependent on the location of the receiver. The raw bin files must be transformed into RINEX format, the industry standard file format, and combined into a single file capturing the whole day in order to remove the biases; a process requiring several softwares. Using Binflate, we transform the files into RINEX, using TEQC we merge the files into twenty-four-hour files, and using GPS-TEC we remove the receiver biases (Seemala, 2023).

2.2 Sidera

Aster Lab's Sidera is a graphical user interface run through MATLAB that uses GPS Ephemeris files to calculate the Earth-centered, Earth-fixed (ECEF) coordinates of every satellite in view of a specified receiver location. The calculated satellite data allows us to choose the time interval for every calculated satellite coordinate for any given date or time of the year. We use the individual satellite datasets to create a single large dataset with every recorded satellite configuration per the requested time interval. Other variables that are included in the dataset are azimuth, elevation, X-Y-Z ECEF, and the PRN (satellite identification number). We use this dataset to calculate the "clear sky" pseudorange offset of each satellite in view of the receiver. This simulated data is important because it gives us a baseline for our pseudorange. Using this data, we can determine the space weather induced pseudorange offset by finding the difference between our "clear sky" baseline and the CASES data from the observed geomagnetic storm.

2.3 Pseudorange Offset & Conversion

Pseudorange is the calculated distance from a satellite to a receiver. The pseudorange formula, (Sickle, 2023), is used to convert the ECEF coordinates of each satellite to a pseudorange value. This value is the distance of a satellite from the high latitude receiver located in Poker Flat. This calculation is necessary as it allows us to calculate the pseudorange offset, which is the difference between two pseudorange values.

The purpose of the pseudorange conversions is to compare the simulated data provided by Sidera to the pseudorange values of the CASES data to determine the magnitude of error caused by the space weather event that occurred on 26 August 2018.

$$P_i = \rho_r^s + c[\delta_r - \delta_s] + d_{trop} + d_{ion} + d_p + \epsilon_{mp} + \epsilon_p \quad (1)$$

The geometric range is the Euclidean distance between the satellite and receiver coordinates at the transmission and reception time, respectively. The pseudorange contains inherent delays which is represented by Equation (1), where P_i represents the pseudorange measurement, ρ_r^s represents the true range, c is the speed of light, δ_s is the satellite clock offset from GPS time, δ_r is the receiver clock offset from GPS time, d_{trop} is the tropospheric delay, d_{ion} is the ionospheric delay, d_p represents the satellite's orbital errors, ϵ_{mp} is the multipath length, and ϵ_p is the noise from the receiver (Sickle, 2023).

2.4 Simulation

Safran's Skydel is a global navigation satellite system (GNSS) simulation software that enables users to simulate position navigation solutions at specified times under specified conditions. For the purposes of this project, we used it to simulate position navigation solutions based on our calculated pseudorange offset measurements. Each satellite has a particular offset in meters at a given time based its position and ionospheric conditions. Skydel works in conjunction with an X300 frequency simulator, and a U-Blox M8 GPS receiver. The X300 allows the U-Blocks GPS receiver to receive the simulated GPS signals, making it experience the same conditions as the CASES receiver in Alaska during the observation period that is being analyzed. U-Center is the native software for the U-Blox M8 GPS receiver and it records data on all inputs that are received, whether from an antenna in real time or from the X300. The deviation charts allow us to plot every position navigation solution in comparison to the objectively set coordinate of the CASES receiver in Alaska. When the objective position navigation solution is set, all the position navigation solutions that are received from Skydel with an offset will be slightly different and will be plotted around the objective position. Once the Skydel simulation concludes, we export the data from U-center for use in correlational studies.

2.5 Correlational Studies

Using navigation solutions provided by Skydel or CASES, the Earth-centered, Earth-fixed coordinates (ECEF) are turned into a measurement of deviation in meters from the actual known point of the receiver. It is, in essence, the Euclidean distance formula. The goal for the correlational study was to evaluate the relationship between ROT and the directionless deviation. Several limiting factors prevented us from conducting the correlational analysis based on simulated data and will be outlined in the discussion section.

$$deviation(t) = \sqrt{(X_t - X_{Actual})^2 + (Y_t - Y_{Actual})^2 + (Z_t - Z_{Actual})^2} \tag{2}$$

(*Euclidean Distance - Definition, Formula, Derivation & Examples*, n.d.)

$$ROT = \frac{dTEC}{dt} \tag{3}$$

(Bolaji, 2023)

2.6 Dynamic Aurora Correlations with Digital Allsky RGB Videos

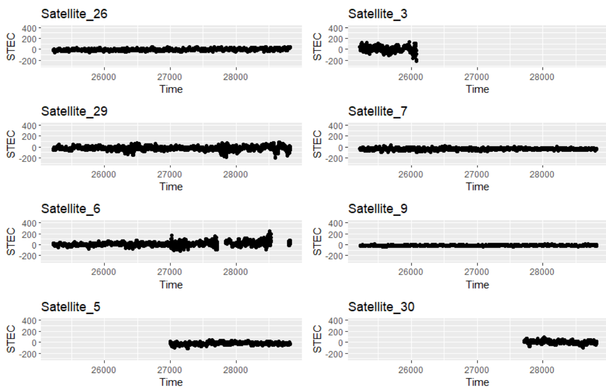
To understand the ionospheric plasma, its relationship to position offset, and the observable phenomenon of discrete aurora, visible imagery is necessary to build a product that shows the aurora and the real-time effects of GPS signal scintillation. The Digital All-Sky Camera (DASC) has a FOV that can observe the complete sky at all times. Red-Blue-Green (RGB) images are compiled around every 11-13 seconds, which can be compiled to create a timelapse video of an auroral event. The use of DASC imagery will give an accurate picture of what a local GPS receiver can receive. A timelapse video that shows the aurora and the satellites with their corresponding scintillation can be created. For the video, a crosshair that changes size and color can best demonstrate the amount of phase scintillation for a given satellite.

The CASES data provides Iq.log and scint.log files that were processed in MATLAB to calculate the Sigma-phi (σ_φ) phase shift of the L1 GPS signal of all active and visible satellites above PFRR. The MATLAB code for calculating the sigma-phi relies on multiple MATLAB support functions. This phase shift data was then processed into a visualization program which takes the DASC RGB imagery video and plots the satellites as crosshairs with varying colors and sizes based on the magnitude of phase shift at that given time along the given satellite path. This video is then qualitatively assessed to demonstrate how an Arctic GPS-user could interpret the problems with their low-grade GPS receiver caused by ongoing auroral activity.

3. Results

3.1 Receiver Bias Removal

The major inhibiting factor in this project was removing receiver biases from the CASES data. The initial direction of our research was centered around evaluating the relationship between slant TEC and deviation in position navigation solutions. This would never have been possible without removing the biases because they come with negative values, which is impossible for a count of electrons between one point and another. Additionally, measurements would be based on one satellite, which does not account for the trilateration of multiple satellites that allows a position navigation solution to be calculated. The use of an industry-known tool, GPS-TEC, allowed us to remove biases and gather a continuous and combined measurement of TEC that can be compared to position solution deviations. The ROT measurements are based on vertical TEC, which is an adjustment of STEC based on the azimuth and elevation of each individual satellite, meaning the variables of azimuth and elevation can be normalized (McGranaghan et al., 2018).



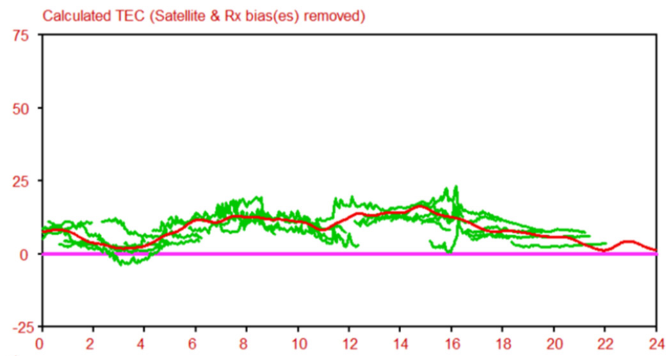


Figure 1 (Left): Biased STEC observations over a window of several hours on 26AUG2018, including all negative values.
Figure 2 (Right): Unbiased VTEC for the entire day of 26AUG2018.

3.2 Pseudorange Offset

We have calculated the pseudorange offset for each individual satellite in a configuration by calculating the pseudorange of each satellite in the Sidera dataset and finding the difference between the solution and the pseudorange provided by the CASES files:

$$r^{(s)} = \sqrt{(x^{(s)} - x)^2 + (y^{(s)} - y)^2 (z^{(s)} - z)^2} \tag{4}$$

(New Mexico Tech)

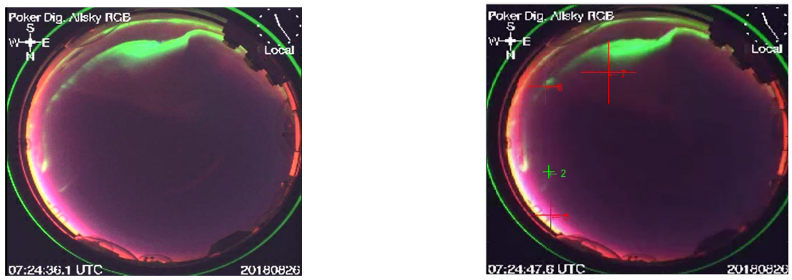
which is the Euclidean distance between a receiver at position (x, y, z) and the satellite, s, at position $p^{(s)} = (x^{(s)}, y^{(s)}, z^{(s)})$.

The margin of error in our results was too significant to be from the changes in the ROT. We concluded that the majority of the “offset” error was a result of the Sidera position solution calculations not aligning with the CASES data from the 26 August space weather event. To ensure that the pseudorange offset values are correct, our future analysis will use the same methodology using different data, not from Sidera, to give us the zero-scintillation data we will use to compare to the high scintillation data from CASES. Since satellites travel in the same path at the same speed throughout the year, we have concluded that it would be more accurate to align the timestamps of a CASES dataset from 25 August 2018, when there was little to no scintillation activity, with the data from 26 August and calculate the pseudorange offset from the two values.

After finding which of the satellites have a significant pseudorange offset, we calculate the coordinates of the satellite using the Earth Centered Earth Fixed (ECEF) coordinate system. This is necessary to determine the direction in which the satellite deviations occur. The results of this analysis will be used to contribute to the pattern recognition of satellite configurations and position solution error that would allow users to predict the direction in which the deviations would occur in the event of a severe space weather event. The magnitude of these deviations could then be utilized in the development of an index to categorize the severity of geomagnetic storms and the effects they have on the operational use of GPS receivers at higher latitudes.

3.3 Dynamic Aurora Correlation with DASC

When observing the DASC imagery for our geomagnetic storm (Figure 3), the deeper hues of green in RGB of the dynamic auroral arcs correspond to higher amounts of scintillation. The color of the auroral arcs shows the composition of the plasma and which region of the ionosphere the plasma is in (CSA, 2022). There are several factors that are associated with auroral motion, none of which have been verified in this study. However, in reviewing the DASC imagery, we discovered a correlation in the motion of the auroral arcs and the magnitude of scintillation. At PFRR, the auroral oval is often observed expanding in the southeast and contracting in the northwest directions. During this process of expansion and contraction, the GPS experiences significant offset due the scintillation that is created in the path of the GPS signal.



(a) (b)

Figure 3: Pre-processed (a) and post-processed (b) still frame of DASC imagery with scintillation data overlayed.

3.4 Relationship Between ROT and Deviation

The initial results of a linear correlation between the ROT and deviation showed no visible trend, so we decided to conduct a probability density analysis at different levels of ROT. The deviations come from the CASES receivers during the observation window and are compared to the ROT at the same time.

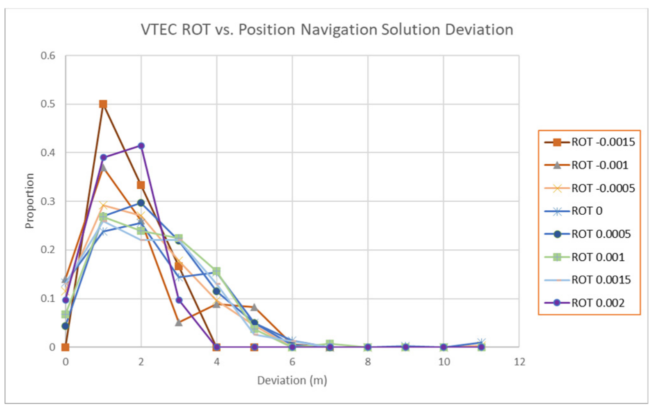


Figure 4: Overlapping probability density curves for ROT in increments of 0.005 TECU/s.

4. Discussion

4.1 VTEC ROT Analysis

The VTEC ROT probability density data shows that there is no significant change in deviation as the ROT changes in increments of 0.005 TECU/s. If there were a significant relationship, it would reflect on the chart in the form of several lines having their curves further to the right, with the peaks centered on a higher deviation. There is still a possibility of correlation if the intervals of deviation are to be made smaller, rounding to the nearest half meter instead of meter. Another factor could be that the dependent variable is a magnitude of deviation, rather than being separated by deviation on each axis. The masking of directional error could be hiding correlations of deviation on a specific axis. The main factor, however, is that high-quality receivers have algorithms that are designed to correct the position navigation solution, which was unknown to us at the start of this project. They are not freely available to access but could potentially be given to a future group through the manufacturer.

4.2 Auroral Analysis from DASC

The MATLAB code to create the video needs development. The problem with this video is that each frame has a pseudo-random timestamp which is difficult to correlate with the data. This means that the current method requires each frame to be logged with the timestamp in a MATLAB script and then run in another MATLAB script to create the video. The pseudo-randomness comes from the fact that the time step is based on fractions of a second between 11.5 to 13.5 seconds. An automated

ISBN: 97819384962-4-0

process of cataloging the frames with a timestamp will need to be produced in order to get data on multiple storms to aid in the sensitivity analysis of space weather impacts on our GPS infrastructure in the Arctic.

Further analysis would include a more detailed analysis of the video product. One method of analyzing of the ionosphere involves dividing sectors of the sky based on elevation and azimuth and generalizing specific sectors that contain discrete aurora. Object-based or pixel-based classification methods could help in generalizing large parts of the sky based on using CASES data as sample points. The DASC imagery at PFRR will be used to conduct this aurora-scintillation correlation. Scintillation is a product of many confounding variables, including change in TEC, but this approximation will make a visual product of elevation and TEC of the ionosphere. Furthermore, models using the Whole Atmosphere Model (WAM) in Systems Toolkit (STK) have been explored for potential use in creating a baseline TEC model to run for the sensitivity analysis. For this project's purpose and time constraints, this method was not used, but it is recommended for future research.

4.3 Future Direction

The development an operational index should be based on industry standard equipment so that stakeholders can use it for a variety of operational purposes. The results of the probability density analysis show that there is a need to analyze multiple variables that contribute to the position navigation solution and not just the ROT. The future of the project should center around simulation to create a controlled environment, and should capture position navigation solutions, azimuths, and elevations on a standardized timeframe for multiple receivers. These datapoints should be combined into a dataset with the auroral analysis in order to be used in deep-learning regression programs. The space community has adopted deep-learning applications in the past several years in order to measure the relationships between the many variables that contribute to observable metrics and this project can be taken in the same direction. An operational index based on formulas derived from deep-learning regression could offer significant correlations that are applicable to multiple receiver types.

5. Conclusion

The significance of research around commercial and military operations the Arctic environment is growing as more users populate the region because of improved access. The mission of this research has not strayed, but the methodology and new insights are constantly evolving. Our new understanding of ROT and receiver biases allows us to continue forward into the simulation element, once again, with the goal of comparing the ionospheric data with position navigation solutions. The efforts now involve cleaning the pseudorange data that will enable our simulator to run, with the results from simulation being put into tools for regression analysis. Based on our current analysis, we have determined that there is a relationship between the direction of the deviation in the position solution and the position of the satellite configuration in relation to the receiver. By analyzing more variables in the data, and incorporating auroral presence, we will eventually be able to predict the direction in which position solution errors will occur for future space weather events.

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