NOAA/NESDIS

Commercial Data Program Space Weather Data Pilot Report

Executive Summary

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Prepared by:

WEIR.PATRICIA.ANN.1367915125
Digitally signed by
WEIR.PATRICIA.ANN.1367915125
Date: 2024.08.26 15:22:35 -04'00'

Patricia Weir
Program Manager, Commercial Data Program
Systems Architecture and Engineering

GASBARRO.MARC.R.1010662911
Digitally signed by
GASBARRO.MARC.R.1010662911
Date: 2024.08.26 15:30:43 -04'00'

Marc Gasbarro
Senior Satellite Systems Engineer
Systems Architecture and Engineering

Approved by:

GRIGSBY.EDWARD.CHAPMAN.1231415137
Digitally signed by
GRIGSBY.EDWARD.CHAPMAN.1231415137
Date: 2024.09.06 16:46:25 -04'00'

Edward Grigsby
Director, Systems Architecture and Engineering

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1. Introduction

The National Oceanic and Atmospheric Administration (NOAA) National Environmental Satellite, Data, and Information Services' (NESDIS) Commercial Data Program (CDP) conducted a Space Weather Data Pilot (SWDP) project in 2022-2023 to explore the feasibility of deriving ionospheric geophysical quantities from commercially-obtained satellite data to help meet current and anticipated needs for space weather observations.

In 2020, the U.S. Congress enacted the Promoting Research and Observations of Space Weather to Improve the Forecasting of Tomorrow (PROSWIFT) Act, setting forth provisions to improve the Nation's ability to forecast and mitigate effects of space weather. PROSWIFT authorizes NOAA to engage the commercial sector specifically to provide space weather data that meets NOAA's standards. On August 1, 2023, Space Sciences and Engineering LLC, dba PlanetiQ, and Spire Global Subsidiary, Inc (Spire) completed their one-year contracts of NOAA's first Commercial Weather Data Pilot for space weather data. The 12-month effort included a three-month preparation phase, a six-month data delivery phase, and a three-month evaluation phase for vendor reachback engineering and technical support. After the contract ended, the SWDP Team continued with their processing, evaluation, detailed assessments, archiving, and documentation of results through April 2024 as well as provided a full report and final recommendations to the Assistant Administrator of NESDIS.

The SWDP Team was managed by the CDP, which is a part of NESDIS' Systems Architecture and Engineering (SAE) Division. The CDP-led SWDP Team consisted of the Space Weather Prediction Center (SWPC) of the National Weather Service, University Corporation for Atmospheric Research (UCAR), University of Colorado, Boulder (UCB), The Aerospace Corporation, NESDIS Office of Common Services (OCS), National Center for Environmental Information (NCEI), European ~~Organisation~~ Organization for the Exploitation of Meteorological Satellites (EUMETSAT), and Boston College (BC). SWPC, as the main end-user of this information, led the pilot's technical aspects. UCAR processed the data and performed data quality analysis. Aerospace, UCB, EUMETSAT, and BC performed data analysis, assessment and evaluation of the vendor data. OCS ingested the data into the NESDIS Common Cloud Framework (NCCF) before disseminating it to UCAR. NCEI archived the data.

In this Pilot study, PlanetiQ and Spire provided six months of near real-time radio occultation (RO) measurements of the ionosphere from their on-board Global Navigation Satellite System (GNSS) receivers that operate in Low-Earth Orbit (LEO). LEO-based GNSS-RO offers a powerful tool for observing ionospheric scintillation, particularly due to its ability to probe the atmosphere along a limb path, providing high vertical resolution data. Three ionospheric products were derived from these data: vertical electron density profiles, slant-path total electron content (TEC), and high-rate scintillation phase and amplitude measurements. The TEC is the total number of electrons present along the signal's path between the GNSS transmitter and RO receiver. Ionosphere electron density profiles (EDPs) are a product derived from the calibrated TEC measurements. EDPs provide the local electron density as a function of altitude, covering the E and F regions of the ionosphere (altitudes of approximately 100-150 and 200-400 km respectively). Scintillation refers to the rapid modification of radio waves when traversing through the ionosphere caused by small-scale electron density turbulence. Scintillation is quantified by two indices: *S4* for amplitude scintillation and σ_φ (sigma-phi) for phase scintillation. These parameters are crucial for high-frequency communication and GNSS applications and help provide insight into near-real-time space weather conditions that impact a wide range of activities, including aviation, precision navigation, and satellite communications.

2. Total Electron Data (TEC)

The SWDP team assessed the quantity, quality, accuracy, validity, latency, coverage, and impact assessment of TEC and EDP data. TEC and EDPs are important descriptive quantities for the Earth's ionosphere. GNSS positioning accuracy depends on the precise determination of the travel time the radio signal takes to propagate from the satellite transmitter to the receiver. TEC improves positioning accuracy for users of GNSS receivers. SWPC takes TEC data and ingests it into their Global TEC model. Currently, they do this for ground stations and Constellation Observing System for Meteorology Ionosphere and Climate (COSMIC)-2 data. However, in order to extend this to vendor data, latency should be no greater than 30 minutes.

The SWDP determined that both vendors provided mostly acceptable TEC data quality. Both vendors exceeded the required quantity of 500 TEC profiles per day. TEC data validated very well when compared with COSMIC-2 data. The SWDP Team determined that the accuracy of absolute TEC from both vendors, measured in terms of uncertainty, was slightly higher than 4.5 TEC units root mean square, which marginally exceeded the threshold of 4 TEC units. In terms of coverage, both vendors provided good spatial coverage, but only one vendor provided decent temporal coverage. This is a function of the differences in constellation size and orbital distribution both vendors operated during the SWDP data delivery time period.

The SWDP conducted an impact assessment of the TEC data. The impact assessment looked at how commercial RO data improved the Global TEC model. These results showed that there is value in adding TEC data into the Global TEC model from commercial RO data as it improved its near-real-time performance. Model bias improved the most away from ground stations, which is an expected result. In addition, ingesting commercial RO data greatly improved the observation density coverage into the Global TEC model, especially away from ground station data.

3. Latency

The SWDP team assessed the latency of both vendors. The Pilot objective was to receive data into the NCCF no later than 30 minutes from time of observation. This requirement matches the latency requirement of TEC data from the COSMIC-2 constellation. Spire succeeded in meeting this threshold with a median latency for TEC data of 29 minutes versus PlanetiQ's 52 minutes. However, the team measured another component of latency: the time it takes to process the data for SWPC's use. The processing time is important in order for SWPC to utilize it for operational purposes, such as their Global TEC model. When factoring in UCAR's extensive processing times from Spire's data, SWPC received their processed data approximately 65 minutes from observation. In comparison, it took UCAR about a third of the time to process PlanetiQ's data. After factoring in data processing timelines, SWPC received PlanetiQ's data about 64 minutes from observation. This dichotomy is due to the way both vendors process and deliver their data. Table 1 lists these details. Latency for scintillation showcased similar results.

Table 1. Daily median Absolute TEC latency for the Space Weather Data Pilot
(Period: Mar 1 - Apr 30 2023)
Product Creation Time is when the product is ready for dissemination to SWPC.

Vendor	Observation to NCCF Delivery Time	Data Check and Dissemination (NCCF to UCAR)	UCAR Processing Time	Observation to UCAR Product Creation Time
Spire	28.6 mins	3 mins	33.1 mins	64.7 mins
PlanetiQ	51.8 mins	3 mins	9.1 mins	63.9 mins

Overall, the Government is confident that both vendors can rectify their latency and processing shortfalls in future efforts as both vendors have implemented some remedies post-pilot. Additionally, TEC accuracy only marginally missed meeting minimum thresholds. The Government is confident that, with close collaboration with the vendors during the data delivery, the vendors can improve their TEC accuracy and latency performance.

4. Scintillation

For scintillation, this pilot evaluated and assessed the utility of commercial RO as well as individual vendor performance. This point is punctuated by the fact that this pilot is the first-ever comprehensive study on using GNSS-RO to sense high-latitude scintillation, whether commercial or otherwise. Detecting ionospheric irregularities from a LEO-based platform using GNSS-RO is challenging. In addition, detecting scintillation at high latitudes presents unique challenges compared to lower latitudes, given the differences in ionospheric physics between the two regions. There were three main challenges for both low and high-latitude detection of scintillation.

The first challenge is accurately determining the location of the ionospheric irregularities (scintillation) along the RO raypath. Geolocation is challenging for scintillation events because scintillation can occur anywhere along the RO raypath from the GNSS transmitter to the GNSS receiver on-board the vendor's platform. A successful geolocation (resulting in a single value) provides a strong indication of ionospheric scintillation. When using GNSS-RO to measure TEC or neutral atmosphere (regions below the ionosphere) parameters, the standard approach is to find the point along the RO raypath called the tangent point to determine observation location. This does not work for scintillation as scintillation can occur anywhere along the RO raypath. Because of this, it was necessary to investigate different methodologies to geolocate scintillation data. The SWDP undertook an evaluation of data for the equatorial regions by comparing geolocations of scintillation events between COSMIC-2 and vendor data. The vendor data compared well for these regions. However, there was not enough time to perform this evaluation for the high latitudes. Future efforts should perform this evaluation. Furthermore, future efforts should include a comprehensive validation of vendor scintillation data compared to ground receivers. These efforts are necessary to establish readiness of vendor data to properly detect scintillation events.

For the second main challenge, the SWDP Team identified a critical shortfall with the requirement-driven scintillation trigger algorithm that determined how much high-rate (50 Hz) scintillation data is downloaded. This algorithm flags data exceeding a predefined scintillation index threshold for downlink, while discarding high-rate data for tracks falling below the threshold. The downlink trigger algorithm plays a critical role in determining which high-rate RO tracks are downloaded from the satellites for further processing and analysis. The commercial trigger algorithm threshold relied solely on elevated scintillation amplitude values, mirroring the approach used by COSMIC-2. This approach works well for the equatorial regions. However, scintillation behaves differently in the high-latitudes. The specific criteria employed by this algorithm impacted the availability of data suitable for scintillation analysis and statistics in the higher latitudes. In other words, the requirement to instruct the vendors to only download high-rate scintillation data that surpassed a certain threshold of scintillation amplitude was too strict, which resulted in missing scintillation events.

To adequately determine the feasibility of the scintillation trigger algorithm, the Government had to assess all data regardless of scintillation amplitude. The Government proceeded by requesting the vendors lift the threshold restriction and download all scintillation data for a 72-hour period. Both vendors graciously provided such data. Analysis of this data confirmed that, in the high latitudes, ionospheric irregularities that cause scintillation were evident with lower amplitude than the scintillation threshold. In addition, analysis showed high-latitude scintillation events dominated by the phase of the scintillation, suggesting that future thresholds consider this as well as amplitude. Further analysis with a more complete data set and with appropriate scintillation-event thresholds is warranted.

The third challenge was identifying data anomalies and discerning anomalous data from scintillation. These spurious features can originate from non-scintillation sources and exhibit signatures in the GNSS-RO observables that closely resemble those of ionospheric scintillation. The SWDP Team revealed the presence of various data anomalies that complicated scintillation detection. An in-depth machine learning algorithm was used to investigate this. The machine learning methodologies performed well in discerning anomalous data and radio frequency interference (RFI) from real scintillation. In addition, the team determined that the vendors can indeed detect real scintillation. Both vendors assisted the team in confirming and identifying potential sources of anomalous data. In addition, preliminary analysis indicated that scintillation geolocation algorithms could be immune to spurious data. Further work is needed to understand the full spectrum of vendor operations in order to delineate all anomalous signatures from scintillation and also to investigate how geolocation algorithms can improve anomaly detection.

In summary, both vendors provided comprehensive data for scintillation. The SWDP Team was able to perform geolocations for available vendor data in equatorial regions, but was unable to perform geolocation validation for the vendor data at higher latitudes. Lack of validation made determining accuracy of scintillation difficult, especially since the SWDP did not obtain an adequate amount of scintillation events. However, geolocated vendor data in the equatorial regions compared well with available COSMIC-2 data. Both vendors were incredibly helpful in volunteering three additional days of data with the lifting of the scintillation amplitude threshold, thus providing all high-rate scintillation data. From this opportunity, the SWDP Team adequately determined that the trigger algorithm was not set properly. Additionally, both vendors were incredibly helpful in responding to questions from the SWDP Team. The technical details gleaned from these answers informed the team on how possible spacecraft behavior and operations contribute to anomalous data.

5. Observations and Recommendations

The SWDP project's success is attributed to the strong collaboration between engineering and science teams. Regular communications ensured project alignment and knowledge sharing throughout the research effort. The interdisciplinary expertise of the team, composed of engineers, data scientists, and ionospheric physicists, played a critical role in achieving these results. Both vendors, Spire and PlanetiQ, were tremendously cooperative in this pilot. This collaborative effort significantly advanced the field of GNSS-RO scintillation detection, paving the way for potential development of near-real-time operational ionospheric products suitable for integration into SWPC's operational systems.

A collaborative effort involving data providers, ionospheric modelers, and operational users is essential to refine the technical data requirements effectively. Future efforts should build upon the successful collaborative efforts from this pilot. This would ensure that the revised requirements cater to the specific needs of near-real-time operational applications while optimizing data acquisition strategies.

Future piloting efforts should consider refining the technical requirements specified in the contract’s statement of work. Recommended requirement updates include optimizing scintillation observation collection to obtain more useful scintillation data, streamlining data delivery methods to acquire and process data in a timelier fashion, and re-assessing TEC accuracy and latency thresholds to potentially incorporate more observations into global datasets for near-real-time operational decision making.

Vendor advancements could help improve ionospheric measurements. Vendor constellation and ground station network updates would improve data latency and temporal resolution. Implementing more streamlined data delivery methods would yield more timely processing of data for operational use. Vendors should strive to reduce events that contribute to RFI, to the extent possible. If not possible, the vendors could work with the Government in furnishing the necessary data regarding spacecraft operations in order to identify anomalous signatures in the data. For future consideration, vendors looking to provide ionospheric measurements with GNSS-RO should plan for high-quality oscillations to optimize collection of high-rate scintillation and high-rate GNSS receivers and antennas to help reduce RFI and other anomalous data.

Future work for TEC should focus on improving latency and accuracy of vendor data in order to utilize operationally into the Global TEC and other ionospheric models. This includes working with the vendors in streamlining their data delivery and data processing algorithms.

Future work for low-latitude scintillation should focus on addressing several areas. This includes providing an in-depth data validation and verification campaign with the updated requirements, enhancing geolocation accuracy, enhancing anomaly identification and mitigation, providing better quality control of datasets, and collaborating on refining end-user products for operational use. By implementing these elements, future piloting could solidify the foundation for reliable low-latitude scintillation products with improved geolocation accuracy, paving the way for their eventual operational implementation.

In addition to recommendations mentioned for low-latitude regions, future work for high-latitude scintillation should focus on robust geolocation techniques specifically tailored to the complex dynamics of the high-latitude ionosphere. These techniques would involve the incorporation of additional data sets from ground-based magnetometers or other space weather monitoring instruments for comparison. Furthermore, a more comprehensive characterization of high-latitude scintillation is warranted. Future efforts would advance understanding of scintillation at high latitudes to include its frequency of occurrence, driving mechanisms, and relationship to geomagnetic effects.

By addressing these key areas, a future pilot could pave the way for commercially-available GNSS-RO data becoming a cornerstone for near-real-time, robust, and reliable operational ionospheric monitoring capabilities. This would ultimately enhance the accuracy of space weather forecasts and provide crucial information for mitigating the impact of ionospheric disturbances on GNSS navigation systems and other technological infrastructure.

6. Summary

This project investigated the feasibility of developing real-time operational ionospheric products from commercial GNSS-RO data, focusing on TEC and scintillation indices. The SWDP Team and NESDIS Management concluded that both TEC and scintillation products from the commercial vendors are *not ready* for an operational environment. However, the SWDP Team and the vendors greatly advanced the readiness of these products. The SWDP Team can advance the ionospheric products to an operational state of readiness by cooperating with the vendors and implementing updated requirements and recommendations in future efforts.

The findings in this report highlight the varying levels of maturity for different aspects of the project, in order of highest to lowest readiness, from TEC to low-latitude scintillation to high-latitude scintillation.

TEC retrievals from RO data demonstrate the highest maturity level within the project. Building upon established techniques and readily-available data processing algorithms, TEC products are considered closest to operational implementation. Further latency optimizations and TEC accuracy improvements are recommended to ensure optimal product performance.

Progress towards low-latitude scintillation products appears promising. However, a more comprehensive validation campaign remains crucial for ensuring product reliability. Latency improvements for scintillation products are aligned with those required for TEC. In addition, work should continue with data anomaly detection and implementing an updated scintillation downlink trigger algorithm.

The understanding and development of scintillation products for mid-latitude and high-latitude regions remain at the nascent stage. These regions present unique scientific and technical challenges owing to the complex nature of the ionosphere at these latitudes. Achieving robust scintillation detection capability at high latitudes with RO measurements necessitates a collaborative effort involving scientists and engineers from various disciplines. In addition, as with low-latitude scintillation, work should continue with data anomaly detection and implementing an updated scintillation downlink trigger algorithm. By addressing these critical areas, GNSS-RO can evolve into a powerful tool for near-real-time monitoring and forecasting of high-latitude scintillation events, ultimately enhancing communication and navigation system reliability in these regions.

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