REPORT TO CONGRESS

COST-BENEFIT ANALYSIS OF NOAA COMMERCIAL DATA PROGRAM RADIO OCCULTATION DATA PURCHASE

Developed pursuant to: Senate Report (116-127) accompanying the Consolidated Appropriations Act, 2020 (Public Law 116-93)

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THE SENATE REPORT (116-127) ACCOMPANYING THE CONSOLIDATED APPROPRIATIONS ACT, 2020 (PUBLIC LAW 116-93) INCLUDED THE FOLLOWING LANGUAGE

NOAA shall provide the Committee with a cost-benefit analysis of the commercial purchase of RO data 180 days after the obligation of these funds.

THIS REPORT RESPONDS TO THE COMMITTEE'S REQUEST.

TABLE OF CONTENTS

I. EXECUTIVE SUMMARY

The National Oceanic and Atmospheric Administration (NOAA) National Environmental Satellite, Data, and Information Service's (NESDIS) Commercial Data Program issued its first indefinite delivery, indefinite quantity (IDIQ) contracts and first delivery orders to procure operational commercial satellite weather data in November 2020 to GeoOptics, Inc. and Spire Global, Inc. These contract awardees provided satellite-based radio occultation (RO) atmospheric profile measurements for numerical weather prediction (NWP) and space weather applications. In March 2021, NOAA issued a second delivery order to GeoOptics for a six-month stream of 1,300 profiles/day to assess the impact of the new commercial RO data on weather forecast systems and test them in operational use.

The initial cost-benefit assessment of the GeoOptics commercial RO data from the second delivery order showed that data were similar in quality to data from some other RO sensors provided by government partners to NOAA, with precision roughly equal to data from the now ended Constellation Observing System for Meteorology Ionosphere and Climate (COSMIC-1) mission and current Korea Multi-Purpose Satellite-5 (KOMPSAT-5) mission; however, significantly lower quality and precision than COSMIC-2 data[1]. Statistically, commercial RO profiles agree well with ground-based measurements, other satellite observations, and model predictions. The impact on weather forecasts was neutral to slightly positive overall, with some analyses showing mixed results with improvement in some areas and degradation in others. An additional analysis indicates that the impact of the commercial data is comparable on a per profile basis to the impact from the most advanced operational RO sensors in use today. Space weather products also showed good general agreement with ionospheric models, and could, pending a sufficient quantity of low latency data, be operationalized in the near future.

A direct comparison of cost between commercially sourced data and data from government assets is not possible at this time, confounded by uncertainty in commercial pricing and varying data restriction policies. However, NOAA compared the anticipated cost per occultation from government-sponsored missions and commercial sourced data procured to date and found that commercially sourced data was about one-quarter to one-half the cost for this delivery order (DO-2). Taking into consideration the differences in cost, precision, and sharing restrictions from the commercial RO data versus data from recent government-sponsored missions, NOAA believes there is value in continuing procurement of commercial data. Based on NOAA's analyses discussed in this report and with confidence in the ability to successfully ingest commercial RO data now established, NOAA has moved forward and purchased a more substantial quantity (3,000 profiles per day) from Spire in a third delivery order running from September 2021 to March 2022. NOAA will continue to monitor and evaluate this commercial RO data stream and tune the forecast systems, as determined beneficial, for increased impact.

[1] *https://www.space.commerce.gov/wp-content/uploads/2020-06-cwdp-round-2-summary.pdf*

II. INTRODUCTION AND BACKGROUND

In November 2020, NESDIS Commercial Data Program issued its first IDIQ contracts for operational commercial satellite weather data. Two vendors, Spire Global, Inc. and GeoOptics, Inc., were awarded IDIQ contracts for NOAA to procure radio occultation (RO) commercial satellite data, consisting of temperature profiles of the atmosphere for NOAA's numerical weather prediction (NWP) systems and ionospheric products for space weather events. This purchase marked the fruition of the Commercial Weather Data Pilot Round 1 and 2 studies, which examined the quality and viability of commercial RO data.

In November 2020 under this IDIQ contract, NOAA purchased 500 profiles per day for one month from each vendor in the first Delivery Order (DO) to develop the systems needed to ingest, process, and distribute the near real-time commercial satellite data. This DO was followed by a second DO, referred to below as DO-2, awarded to GeoOptics in March 2021 to deliver 1,300 profiles per day for six months. Both DO-1 and DO-2 had data sharing restrictions, which allowed for near-real-time access to NOAA and other U.S. federal agencies only. All others, including international partners and the broader weather enterprise did not have access to this commercial data until 24 hours after data was acquired. This delivery was used to assess the quality and viability of commercial RO data for operational use in NWP models. These data form the primary basis for the cost-benefit analysis presented in this report.

The DO-2 data were fed into a test environment at the NOAA Environmental Monitoring Center and monitored for 49 days to ensure operational weather forecasts would not inadvertently be degraded or disrupted by the data. Upon successful conclusion of this test in May 2021, commercial RO data were deemed acceptable for operational use, and for the remainder of the six-month period the data were used in operational NWP.

This report summarizes the assessment performed on DO-2 data, where NOAA compared the quality of this commercial data to other operational sources, gauged the impact on weather forecasts, and investigated its potential for use in future space weather applications.

III. DATA QUALITY AND IMPACT

A. Data Quality Requirements

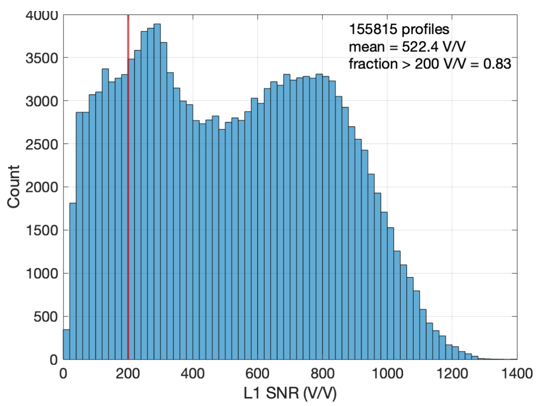
The IDIQ contractual requirements for commercial RO data stipulated several general quality measures be met. Compliance requirements for each individual profile are:

- **Latency:** Data must be delivered to NOAA within 140 minutes of profile observation time.
- **Signal-to-noise ratio (SNR):** The SNR of a profile, averaged over the 60 to 80 km region, must be at least 200.
- **Extent:** A profile's altitude extent must span the range from –150 to 90 km in terms of the straight line-of-sight altitude.

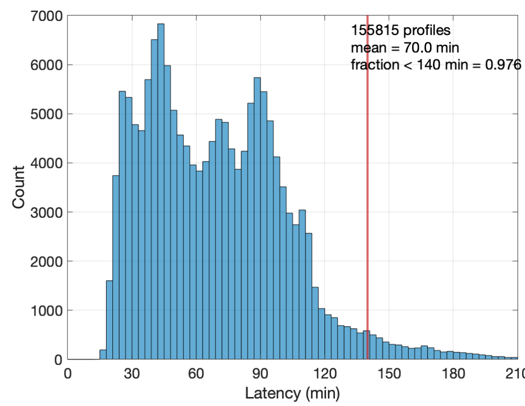
Aggregate requirements on ensembles of profiles are:

- **Quantity:** For DO-2, an average of 1,300 compliant profiles per day with no more than 3 days less than 1,170 profiles (90 percent) was required for every 30-day period.
- **Geographic distribution:** The spatial sampling of the profiles must be globally distributed in latitude and longitude.

Data were also required to come from a pre-approved list of commercial satellites and use signals only from healthy global navigation satellite system (GNSS) transmitters. Initially for DO-2, including the data period examined in this analysis (April 2 to May 20, 2021), GeoOptics met all the above data quality requirements. In June 2021, one of three GeoOptics satellites for RO data was lost and the daily quantity dropped beneath the requirements. However, all other data quality requirements continued to be met or exceeded.

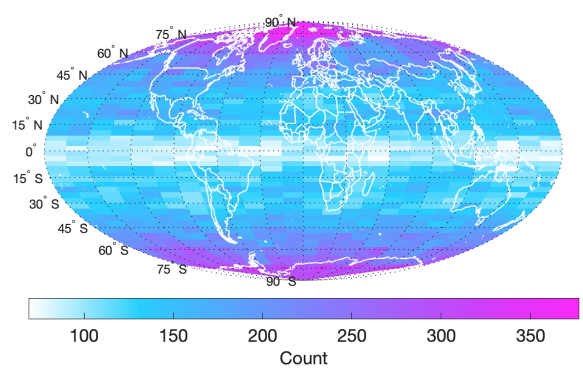


(a)



(b)

Figure 1. *DO-2 quality metrics for the period of March 18 to July 31, 2021.* ***a)*** *Distribution meeting signal-to-noise ratios (SNR) requirement for the L1 frequency band of 200 or greater (right of red vertical line).* ***b)*** *Distribution meeting latency requirement of 140 min or less (left of red vertical line).* ***c)*** *Geographic distribution of DO-2 observations meets requirements and is complementary to the COSMIC-2 data, which provide tropical and midlatitude coverage only.*



(c)

B. Data Quality Analyses

A standard method of monitoring observational data quality is to compare them with operational model forecasts. Applying this technique, differences were found between observed RO profiles and RO profiles modeled from the state of the atmosphere at the time and place of the observation as given by the Global Forecast System (GFS) operational output. The differences between the observed and modeled values were assembled and the mean bias and root mean square error (RMSE) were computed and normalized by the model value. This comparison is referred to as observation minus background.

For the period used for the NWP impact assessment (April 2 to May 20, 2021), the global observation minus background statistics for the commercial data show only a very small mean bias, indicating good accuracy. The RMSE is also relatively small, indicating reasonable precision, although it is slightly higher than seen in other missions, such as KOMPSAT-5, a Korea Aerospace Research Institute mission. When looking at various regions, the RMSEs are similar in the Northern and Southern Hemispheres, but are slightly larger in the tropics, indicating some reduced precision. This result is typical for RO observations because of interference from finescale variations in water vapor concentration in the tropical troposphere. The observation minus background global and tropical region results are depicted in Figure 2.

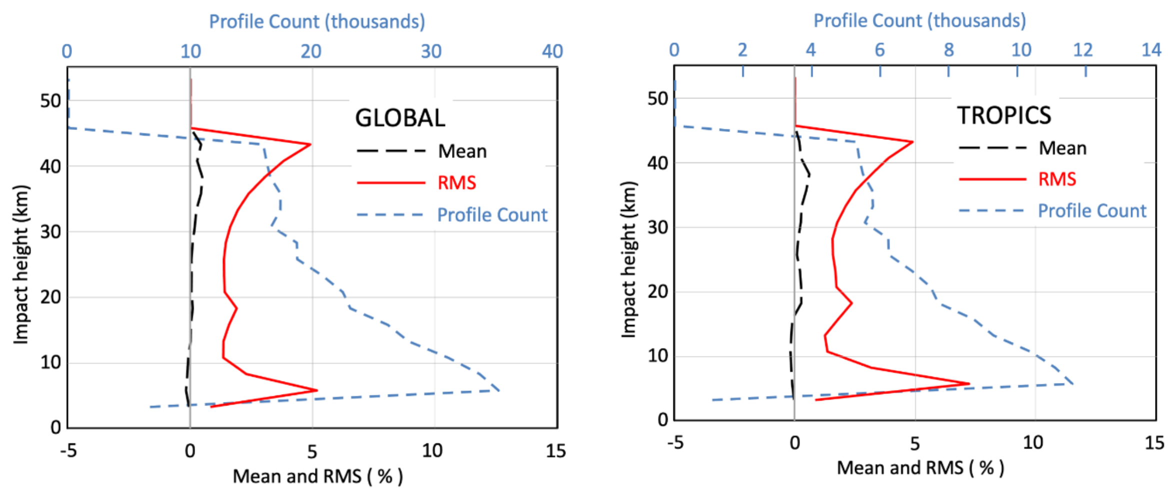


Figure 2. *Comparison of DO-2 commercial RO data to model data for the period of April 2 to May 20, 2021 via Observation-minus-Background (OMB) statistics. Both graphs show the mean bias (black line) indicating the degree of agreement with the model (accuracy); the RMSE (red line) indicating precision or variability (lower is better as plotted against bottom axis); and observation count (blue line, as plotted against top axis). Each value is plotted versus impact height (y-axis), which is approximately equal to the altitude of the RO data being observed. The left panel shows results for all data (global), and the right panel shows results for the tropics only. These results are similar to statistics seen in most operational RO missions.*

Beyond initial compliance checks as described above, RO data continually undergoes a series of quality control procedures prior to being assimilated into the forecast system. The most revealing of these is a background check which involves the observation minus background comparison described above. Statistics from this check can provide an indicator of overall quality of the dataset. For the DO-2 data used in the impact study (April 2 to May 20, 2021), there was an average of about 8 percent rejected by the background check. For comparison, about 4 percent of KOMPSAT-5 RO data are rejected. KOMPSAT-5 has RO data of similar quality to the DO-2 commercial RO data, products generated by University Corporation for Atmospheric Research, and data ingested into NWP systems since 2014. Therefore, KOMPSAT-5 provides a basis of reference for evaluating new RO data sources of similar quality.

C. IMPACTS ON FORECASTS

The impact the observations have on the forecast is the primary metric for assessing their value to NWP. To gauge the impact of the DO-2 data, we compared the operational forecast without the DO-2 data and an experimental forecast, which used the DO-2 observations, to radiosonde observations. A statistical analysis of the differences was conducted, and the forecasts were ranked according to selected verification metrics. The results of the analysis are synthesized into visual "scorecards" that summarize the forecast improvements and degradations resulting from the assimilation of DO-2 data, shown in Figure 3. The statistics are broken down by forecast variable (temperature, wind, humidity), by region, and by pressure level. Even though RO is essentially a temperature measurement, assimilating the observations can impact all forecast parameters, including wind and humidity. Figure 3 is a visual interpretation of the statistical analyses with the scorecards showing that the DO-2 data had an overall beneficial impact in reducing the model bias, but reveals increased variability (RMSE), indicating degraded precision. The impacts on different regions are somewhat contrasted. The assimilation of DO-2 data tends to increase the temperature and wind RMSE in the Northern Hemisphere, including North America, but slightly reduces the temperature RMSE in the tropics. The amplitude of the temperature RMSE difference is very small: less than 0.1°C at any level and for any lead time. Similarly, the amplitude of the wind RMSE differences is less than 0.5 m/s at any level or lead time.

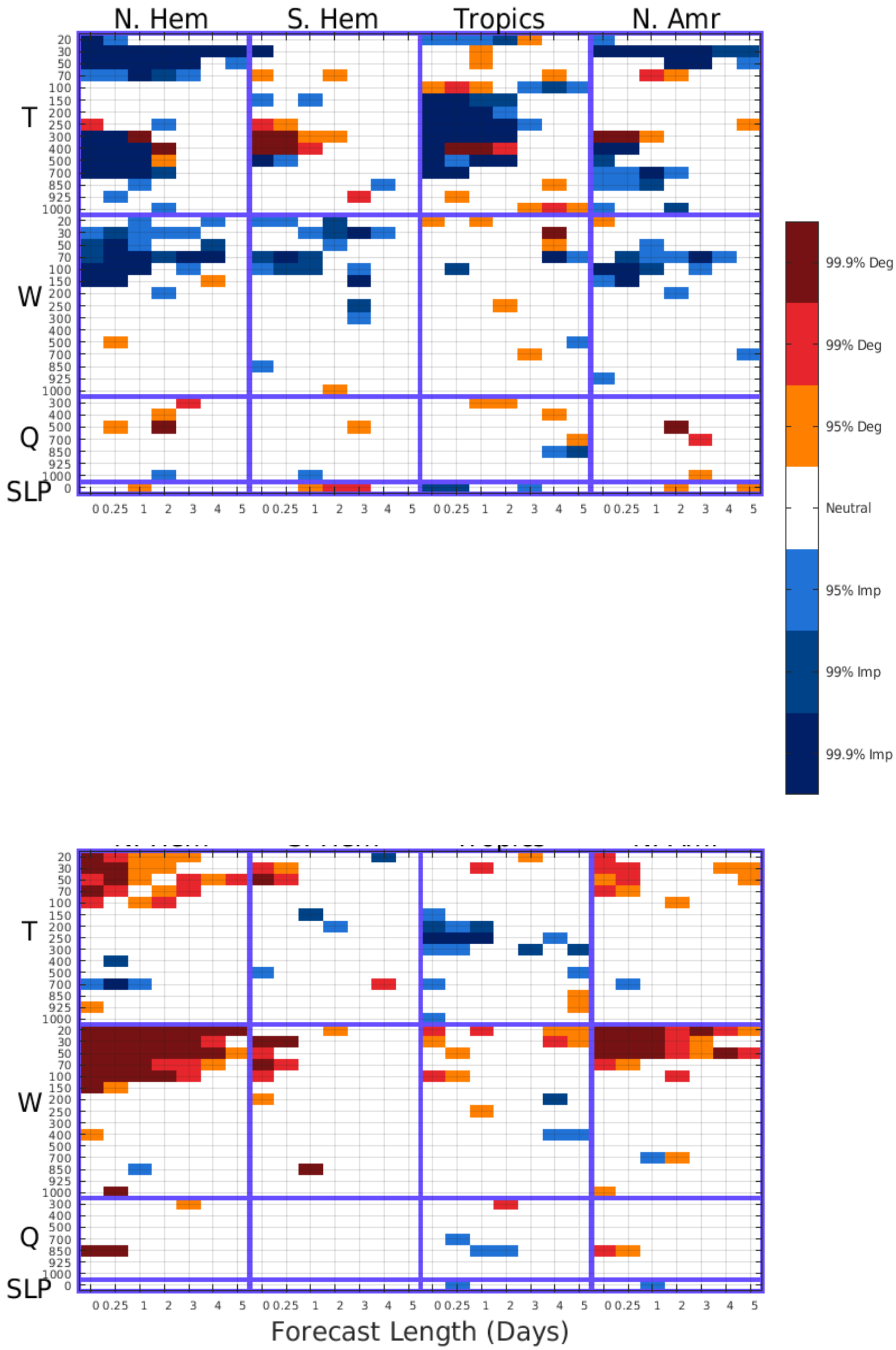

N. Hem
S. Hem
Tropics
N. Amr
T
W
Q
SLP
99.9% Deg
99% Deg
95% Deg
Neutral
95% Imp
99% Imp
99.9% Imp
Forecast Length (Days)

Figure 3. *DO-2 forecast scorecards verified against radiosonde data. Top: Average bias. Bottom: Average RMSE. T = temperature; W = wind; Q = humidity; SLP = surface level pressure. Pressure in hPa is listed as the vertical coordinate. Colors indicate statistical significance of the result with warmer colors showing regions of forecast degradation ("Deg") and cooler colors showing forecast improvement ("Imp") for the Northern Hemisphere, Southern Hemisphere, Tropics (23.4°N to 23.4°S), and North America (left to right).*

While radiosonde data provide an excellent standard to compare forecasts against, they are limited to specific locations and are not global in nature. Global evaluation can be accomplished by comparison against a model analysis. To examine the global performance, the European Centre for Medium-range Weather Forecasts (ECMWF) operational analysis was compared to the GFS model including commercial RO data, since both models are independent from each other. Overall, the analysis of commercial RO data with ECMWF showed similar results to the analysis of commercial data with radiosondes. Both analyses showed mixed results with improvement in some areas and degradation in others, but the amplitudes of the observed differences were all very small, for both temperature (less than 0.1°C) and wind (within 0.5 m/s). Such mixed results are not uncommon for newly ingested data sources, as the system has not yet been tuned to the specific characteristics of this commercial RO data, and the quantity of profiles used in the test was somewhat limited due to time constraints for analyses.

In an independent assessment, the U.S. Navy conducted daily Forecast Sensitivity Observation Impact (FSOI) experiments to assess the relative contributions of the DO-2 GeoOptics data. Higher FSOI scores indicate better performance. They began to operationally use the commercial data in May 2021. Initial FSOI results are shown in Figure 4, comparing the DO-2 data (labelled Cicero) to other RO missions that were operational during the month of June 2021. One of the DO-2 GeoOptics satellites (Cicero-4) stopped operating during the period and results are therefore poor for this instrument, but the other two (Cicero-1 and Cicero-3) have similar scores and outperformed all but the Meteorological Operational Satellite Program of Europe-A (Metop-A) and TerraSAR-X Digital Elevation Measurement (TanDEM-X satellites). TanDEM-X data, however, are very sparse and should not serve as a reference. This indicates that the DO-2 observations' quality is comparable to those from the most advanced operational RO sensors in use today. It should be noted that the assimilation algorithms for COSMIC-2 data have recently been updated to include several fixes and improvements, so their FSOI scores are likely to significantly increase over the values reported in this analysis.

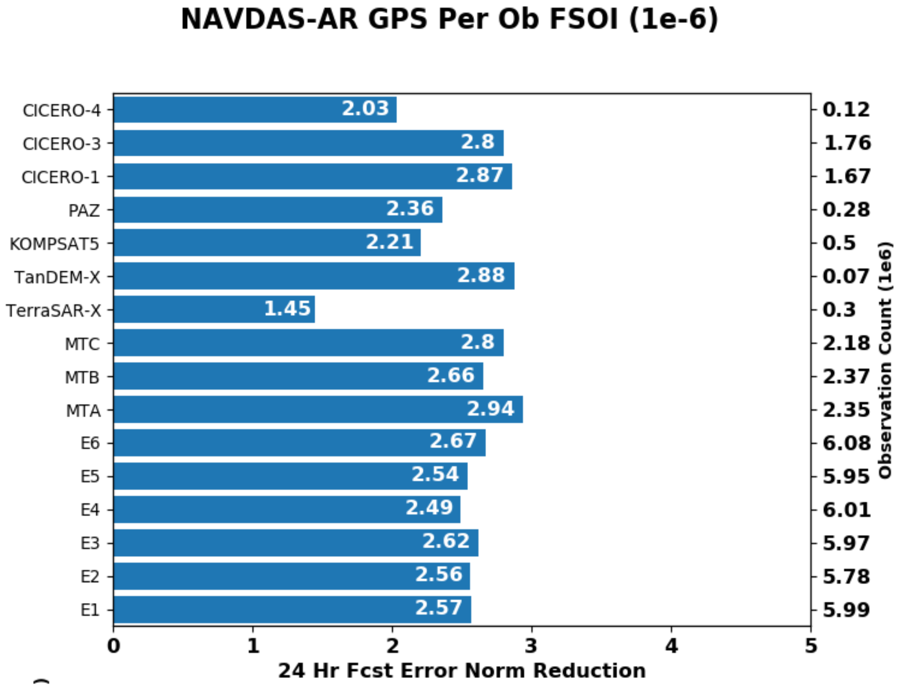


Figure 4: *FSOI for each RO satellite operational at U.S. Naval Research Laboratory in June 2021. Higher FSOI values along the x-axis indicate better performance. The mean observation count is provided for each satellite on the right axis. GeoOptics satellites are labelled CICERO 1, 3 and 4; COSMIC-2: E1 – E6; MTA, MTB, MTC are the MetOP satellites; Paz is the Spanish RO satellite. During this analysis period, as seen by a higher 24 Hr Error Norm Reduction (x-axis), DO-2 RO data outperformed many other operational RO data sources.*

D. Space Weather Assessment

The NOAA Space Weather Prediction Center (SWPC) is evaluating the DO-2 data for potential use in space weather applications. This includes the total electron content (TEC) ionospheric product derived from the DO-2 data. TEC is the total number of electrons per unit area along a path between the GNSS satellite and the RO satellite. A global TEC model (GloTEC) has been established at SWPC to produce a real-time global ionospheric electron density specification based on RO and ground based observations. GloTEC helps identify abnormal ionospheric conditions that affect radio signal propagation, providing improved space situational awareness in support of critical communication systems. A parallel experimental version of the GloTEC system has been ingesting the new commercial RO TEC data since the initiation of DO-2 on March 17, 2021.

GloTEC runs are executed every 10 minutes using three data configurations: ground-based data only, commercial RO data only, and ground-based plus commercial RO data. The general methodology is to examine regions where RO and ground-based TEC both have dense coverage in time and space. If the resulting TEC from the RO ingestion agrees with the state-of-the-art ground-based TEC product in these overlapping regions, then the RO TEC data are considered reliable and can be used where no ground coverage is available. By comparing vertical TEC derived from the GloTEC electron density state where both ground-based and space-based data coverage are of sufficient quality, the level of agreement between the two assimilated electron density states can be analyzed.

In doing so, SWPC can justify the use of the RO data where ground-based coverage is lacking, which can improve the model's global GNSS data coverage, especially over the oceans and regions with few GNSS stations or without real-time data dissemination capabilities.

The ingestion of DO-2 TEC data into the GloTEC model showed good agreement with the TEC outputs in regions with overlapping coverages from RO and ground-based TEC data. However, the overall quality and latency of the DO-2 measurements have been marginal for inclusion in the SWPC GloTEC product. The ingestion of commercial RO data can benefit SWPC's operation with an increase in global coverage relative to ground-based data alone, but latency of less than 30 minutes is required by operational models given the rapid variability of the ionosphere. Also, absolute TEC measurements from the RO antenna are currently not being produced due to the lack of overlap in measurements from the Precise Orbit Determination (POD) and RO antennas. Consequently, only a limited amount of lower elevation scans across the ionosphere from the POD antenna are currently being used, less than 5 percent of the received TEC, which results in a significant fraction of the ionosphere not being observed.

IV. COST-BENEFIT COMPARISON

As discussed above, the primary benefit of commercial RO data will be the realization of improved weather forecasts. In addition to providing another source of direct observations, RO data are unbiased in nature, which allows NOAA to better exploit other key observations that require bias correction, most notably radiances. The degree to which the commercial RO data will help the forecasts is not yet fully quantified, but based on the preliminary analyses discussed above, they will yield a similar effect on forecast models as other operational RO data sources. Their benefit is expected to scale with the quantity ingested, at least for quantities up to an additional 10,000 profiles per day to total approximately 20,000 profiles per day[2]. Other anticipated benefits come from space weather events. The space-based RO data are complementary to ground-based GNSS data, and they provide measurements in regions where ground-based receivers are unavailable. This has the potential to improve space weather nowcasts and forecasts at all global locations where impacts to navigation and communication systems occur.

Additional benefits of commercial RO data include the important role of these data in risk reduction against the loss of other observational capabilities. Satellite systems are inherently subject to potentially irrecoverable failures. Such failures are anticipated to become more frequent with the reliance on smaller instruments flying on satellites with shorter design lifetimes. Maintaining a robust portfolio of overlapping and complementary observation sources reduces the overall risk to the users' systems should one source become unavailable.

The benefits and relative costs of commercially provided data appear to be favorable based on preliminary analyses, but additional analysis is needed to better understand how factors related to the commercial marketplace, supply chain vulnerabilities, and changes in the competitive

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[2] *Harnish et al. (2013)* *https://journals.ametsoc.org/view/journals/mwre/141/12/mwr-d-13-00098.1.xml*

landscape can impact price fluctuations and/or affect the quantity of data available for purchase and make maintaining a consistent data flow – a requirement for operational weather forecast systems.

For a cost comparison, the COSMIC-2 mission provides the most relevant reference. This is the most recent NOAA and partner sponsored RO mission, and is producing approximately 6,000 RO profiles per day for an estimated total development to launch cost of $230 million with $10 million in annual operating expenses, including contributions from all partners, and assuming a life of fifteen years. Taking all costs by NOAA and partner entities into consideration, cost per occultation range are:

COSMIC-2 Cost per occultation range:

Assumed average lifetime of constellation	Cost per occultation
5 years (design life)	$25.55
15 years (maximum life)	$11.56

The DO-2 commercial data were acquired for approximately one-quarter to half of the COSMIC-2 price. However, while COSMIC-2 and the commercial vendors all produce operational-quality RO products, there are some significant differences, most notably COSMIC-2's high precision and open access data dissemination to all users in near real-time. The DO-2 commercial data were purchased with sharing restrictions that only allow near-real-time access to NOAA and other U.S. federal agencies. Implementing these restrictions required NOAA to develop customized systems and processes specific to these restricted data, and more importantly, jeopardized the benefits NOAA currently receives from international data sharing agreements. Based on the ceiling prices proposed by the vendors, the estimated cost for unrestricted commercial data would have been 65 to 85 percent higher than the DO-2 purchase price.This is only a projection, and the commercial sector will set the actual prices for the data within the limits defined in the IDIQ contract.

NWP models have not yet been tuned to extract the maximum information from each specific RO system; they generally treat all RO sources the same. COSMIC-2 data has a significantly better SNR ratio (better precision) than the current commercial data (SNR of COSMIC-2 is 1513 and GeoOptics DO-2 is 522). Commercial RO data has poorer SNR (less precision) limiting the usefulness of the commercial data in the lower troposphere. Data from this part of the atmosphere are critical for more accurate precipitation forecasts and the forecasts of extreme events (like hurricanes and fire weather). However, even without these lower tropospheric data, including the commercial RO data in our models showed mixed results implying a neutral to slightly positive impact related to the general prediction measures used to measure overall forecast skill. As NWP models are refined it is expected that the higher precision measurements will yield increased benefits, especially in the important lower troposphere.

V. CONCLUSIONS

Since November 2020, two commercial satellite data providers, GeoOptics and Spire, have IDIQ contracts with NOAA and have been competing for delivery orders to provide satellite-based RO atmospheric profile measurements for numerical weather prediction and space weather applications. After acquiring small data samples from each vendor, Delivery Order 2 (DO-2) was awarded to GeoOptics, in March 2021, for six-months of data to assess the impact and ensure the data are suitable for operations. The commercial RO data were found to be acceptable, and operations commenced in May 2021.

An analysis of data from April 2 to May 20, 2021, showed that commercial RO profiles were found to agree well with ground-based measurements, other satellite observations, and model predictions. The initial data assimilation test, comparing forecasts with and without the commercial data, showed mixed results implying a neutral to slightly positive impact with only very small amplitude changes, as anticipated given the relatively small quantity of data. Larger quantities of RO data are expected to have more significant impacts on the forecast models.

Data has been shared with U.S. Government partners, and the U.S. Navy conducted an independent assessment which showed a positive impact. They, too, have operationalized these data. Space weather products, examined by NOAA's Space Weather Prediction Center, showed good general agreement with ionospheric models. Indirect benefits of commercial RO data include risk reduction against loss or reduction of existing observational capabilities and, if sufficiently broad licensing terms are acquired, are helping to continue data-sharing practices with NOAA's partners in the meteorological community and ensure public access to forecast-critical data.

Current commercial prices are less than COSMIC-2, but the data are of lower quality and contracts include sharing restrictions which make a direct comparison between government assets and commercially sourced data impossible. Unrestricted commercial data has not yet been purchased, but the vendors' proposed price caps for unrestricted data are significantly higher, and potentially higher than COSMIC-2 prices.

The commercial RO data have now been deemed acceptable for operations and have become part of NOAA's portfolio of environmental data sources. As of September 2021, DO-3 is providing a more substantial quantity of data (3,000 profiles per day) from Spire Global for six-months (September 2021 to March 2022). During this period, NOAA will continue to assess the commercial RO data stream for quality and impact, along with our scientists and engineers tuning the forecast systems to extract increased benefit from these data.