Commercial Satellite Data Acquisition Program

GeoOptics Principal Investigator Evaluation Summary

Goddard Space Flight Center
Greenbelt, MD

Commercial Satellite Data Acquisition Program GeoOptics Principal Investigator Evaluation Summary

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Preface

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Abstract

The evaluation summarized in this report was conducted by Principal Investigators (PIs) funded by NASA's Commercial Satellite Data Acquisition (CSDA) Program. The purpose of the evaluation is to determine the utility of the GeoOptics data for the NASA Earth science research and applications community. The results of the evaluation help to inform NASA program management on the ability of the data to further augment NASA science.

Cover Art: Cover art is AI generated graphic using Microsoft Copilot Designer using term "commercial satellite constellation Earth observation across Atlantic AND Northern Hemisphere AND digital downlink"

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Change History Log

Revision	Effective Date	Description of Changes
1.0	09/08/2025	First reviewed version for public release complete
0.2	5/30/2025	Revised Draft Completed
0.1	12/09/2024	First Draft Completed

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Executive Summary

NASA's Earth Science Division (ESD) Commercial Satellite Data Acquisition (CSDA) Program selected 7 principal investigators (PIs), along with their teams, via a call for proposals under the NASA Research Opportunities in Space and Earth Science (ROSES) solicitation, to evaluate GeoOptics, Inc. (also referred to as GeoOptics) as part of the third CSDA on-ramp. GeoOptics had a constellation of its CICERO satellites that collects measurements from the U.S. Global Positioning System (GPS) as well as other Global Navigation Satellite Systems (GNSS).

GNSS radio occultation (RO) measurements offer an innovative remote sensing technique for measuring atmospheric parameters such as refractivity, temperature, water vapor and pressure and have been used to improve numerical weather prediction (NWP) and other global climate monitoring. GNSS RO have several characteristics such as global coverage, long-term stability of observations, as well as high vertical resolution of the derived atmospheric profiles. For these reasons, NASA funded several investigations into the utility of these data for NASA Earth system science research and applications. Over the span of a year, seven Principal Investigators (PIs) from NASA Research and Analysis science focus areas—specifically, weather and climate—were engaged to evaluate GNSS radio occultation data from GeoOptics. During this CSDA evaluation, the teams evaluated GeoOptics data across multiple Earth science disciplines, including Weather and Atmospheric Dynamics, Upper Atmosphere Research, Satellite Data Assimilation, among others.

The vendors participating in the CSDA Program are evaluated on the accessibility of vendor supplied data, accuracy and completeness of metadata, quality of user support services and documentation, usefulness of the data for advancing Earth system science research and applications, and the quality of vendor supplied data. Datasets purchased during the evaluations are archived by NASA and the evaluated data are available to current and future government-funded researchers in accordance with the end user licensing agreement (EULA). The GeoOptics data were evaluated in the context of a variety of research topics (see Table 2 and the Appendix).

The GeoOptics evaluation kicked off with a first team meeting in January of 2023. Data access began in May 2023. This synthesis report distills and integrates the findings of research reports commissioned by NASA for the GeoOptics evaluation. This report also includes recommendations that inform the way forward for these data within the program.

The report finds several strengths and weaknesses of these data for use in NASA Earth System Science and applications investigations. The evaluation teams encountered numerous limitations that diminished the utility of some aspects of the data. For example, the GeoOptics Level 1b data processing algorithms limit the lower troposphere sensing for planetary boundary layer applications. Additionally, the effort needed to preprocess, interpret and analyze the data, due to of their unconventional organization, as well as documentation and metadata issues, increasing the data processing complexity.

Overall, the utility of the GeoOptics data, in addition to their polar coverage, outweighed the difficulties encountered, and it was determined that the GeoOptics GNSS Radio Occultation data would complement NASA and other existing RO satellite system capabilities. The evaluation team recommended that GeoOptics improve their processing algorithms—especially for the lower troposphere—to enhance their use for planetary boundary layer studies. They also emphasized a desire for future GeoOptics instruments to capture low-elevation ionospheric measurements and strengthen ionospheric research.

1. Background

NASA's ESD formalized the CSDA program in 2020, following the successful Private-Sector Small Constellation Satellite Data Product Pilot that concluded that year. The objective of the CSDA program is to identify, evaluate, and acquire commercial remote sensing data that support NASA's Earth science research and application activities. When the Pilot transitioned into the sustained CSDA Program, on-ramping opportunities were released for new vendors with the idea of expanding the program and enlisting new commercial vendors as the industry expands with new candidates and capabilities. NASA's ESD recognizes the potential impact commercial satellite constellations may have in encouraging and enabling efficient approaches to advancing Earth system science research and applications development for societal benefit.

In addition to the Pilot, NASA has conducted two evaluations since the Pilot, these included two vendors in the Blanket Purchase Agreement (BPA) On-Ramp 2 and four vendors in the BPA On-Ramp 3. GeoOptics was part of On-ramp 3, and the three other vendors in this On-Ramp were wrapping up their evaluation activities in a similar timeframe as GeoOptics.

NASA has moved into a sustainment phase for the vendors from the Pilot and BPA On-Ramp 2 with data collected by these vendors made available to NASA and other government funded researchers, according to the EULAs. More information can be found on the CSDA web site, under Commercial Datasets. The table below shows the vendors that NASA has engaged with for commercial data evaluations thus far.

Table 1. CSDA Evaluation Activities.

Evaluation Effort	Vendor	Type	Report Delivery
Pilot	Maxar	Optical	Apr 2020
	Planet	Optical	
	Spire	Radio Occultation	
On-ramp 2	Airbus U.S.	SAR	Oct 2023
	BlackSky	Optical	Jun 2024
On-ramp 3	GHGSat	Optical	Aug 2024
	Capella	SAR	Dec 2024
	ICEYE U.S.	SAR	Dec 2024
	GeoOptics	Radio Occultation	Oct 2024
IDIQ On-ramp 1	Umbra	SAR	Aug 2025
	PlanetiQ	Radio Occultation	Aug 2025

The vendors were evaluated on the accessibility of data, accuracy and completeness of metadata and documentation, promptness and quality of user support services, and usefulness of the data for advancing Earth system science research and applications. NASA's CSDA Program license agreements were expanded following the Pilot to broaden the applicability of the commercial data for scientific applications across the U.S. Government. These license uplifts made the data more readily available across the government and improved both the value of these data and the opportunities for interagency collaboration. In addition, NASA has engaged in separate dedicated evaluation activities to assess the satellite data quality of each vendor.

Results from the Pilot and the On-Ramp 2 evaluations are available from the CSDA website. The final summary reports for all the On-Ramp 3 evaluations will also be published on the CSDA web site upon completion and review of the evaluation reports.

1.1 BPA On-Ramp 3

On-Ramp 3 evaluations were initiated in October 2022 with a request for information (RFI) seeking capability statements from the parties interested in providing data from spaceborne platforms for evaluation. To be responsive to the RFI, the commercial satellite vendors had to be U.S. companies with one or more spacecraft actively collecting data in low, medium, or geostationary Earth orbits with a minimum of near-continental-scale–coverage. Four vendors satisfied the RFI requirements and were asked to respond to a request for proposal. After review of the submitted proposals, NASA entered into a BPA with GeoOptics, Inc. in September 2022. The vendors evaluated during On-ramp 3 are listed below in Table 2.

Table 2. The vendors and sensor information for CSDA On-ramp 3 evaluations (constellation numbers reflect status during the evaluations).

Vendor	Sensor Type	Temporal Coverage	Spatial Coverage	Satellites	Bands	Spatial Resolution
GHGSat	Optical	Jan 2021 - present	Global	10	1630 – 1675 nm	< 30 m
GeoOptics	GNSS-RO	Nov 2018 – Jan 2022	Global	0	L-Band	~100 km horizontal, ~100 m vertical
Capella Space	SAR	Jan 2021 - present	Global*	4 - 7	X - Band	0.5 - 11.5 m
ICEYE US	SAR	Oct 2019 - present	Global	13 - 21	X - Band	1 - 15 m

*****_During the evaluation period, Capella lost its only polar orbiting satellite sensor, thus access to data over areas beyond 48.9 deg N/S were limited._

1.2 GeoOptics Capabilities and Products Evaluated

The GeoOptics CICERO constellation consisted of several 6-unit (6U) nanosatellites in various low Earth orbits (LEO) below 600 km. The CICERO satellites were identified by their number (085, 086, 087, 088), with the exception of file formats with specific definitions for spacecraft identification (e.g. BUFR). Note that only three of their nanosatellites (085, 087, 088) were included in this evaluation.

The University Corporation for Atmospheric Research (UCAR), in Boulder Colorado, is a non-profit consortium comprised of over 130 North American universities doing Earth system science and research. The UCAR constellation observing system for meteorology ionosphere and climate (COSMIC) program has been the leader for retrieval and application of Global Navigation Satellite System (GNSS) data since the 1990's. In contrast to the early high-end GNSS receivers used in the COSMIC and COSMIC-2 missions, GeoOptics employs relatively low-cost, low-power and lightweight receivers for RO measurements. These receivers are capable of tracking GNSS signals from both U.S. global positioning systems (GPS) and the Russian Global Navigation Satellite System (GLONASS).

Over the period from 01-Jan-2020 to 30-Apr-2021, GeoOptics provided data products across all levels, including Levels 0, 1a/1b, and 2, which provided comprehensive resources for analysis (see details in Table 3). Note that Level 0 data were not evaluated, and the Level 2 data included both ionosphere and neutral atmosphere data products. Out of a total of 486 days, two satellites (085 & 087) provided data throughout the whole period, whereas satellite 088 only had data from the end of 2020 to the end of April 2021 (140 days).

Table 3. CSDA GeoOptics Data Product Summary.

Processing Levels	Data Products
Level 0*	Raw open loop/close-loop phase & attitude measurements
Level 1a	Antenna Parameters (podObs)
	LEO attitude data (leoAtt)
	RO datasets, high rate 50 Hz (opnGns)
Level 1b	LEO POD data (cicPOD, orbits and clock biases)
	Atmospheric excess phase (cicPrf, cicPOD)
	Signal-to-Noise Ratio (opnGns, cicPOD)
Level 2 (Atmospheric Data)	Bending angle, refractivity, dry pressure and dry temperature (cicPrf)
	Water vapor, temperature and pressure (1DVar)
	BUFR data
Level 2 (Ionospheric Data)	occTec (TEC at a negative elevation angle from POD antenna)
	podTec (TEC at a positive elevation angle from POD antenna)

*** Level 0 data were received but were not evaluated.**

GeoOptics Level 1a data comprised three file types, leoAtt (LEO attitude data), opnGns (high-rate data in opnGns format with distinct files for each downlink), and podObs (RINEX3 observation data from the side-looking precise orbit determination [POD] antenna). The Level 1b (excess phase and signal-to-noise ratio) files contain an average of ~600 daily RO profiles for each satellite, for a total of 616,986 measurements. Among the data, 393,860 (64%) measurements contain both the excess phase and successful Level 2 bending angle/refractivity profiles. The remaining 223,126 measurements contained only excess phase data, failing to retrieve Level 2 profile data. Similarly, about 30% of all occultations (occTEC) were contaminated with ultra-high frequency (UHF) radio interference, which, according to the documentation (GeoOptics, 2023a) was stated to be a minor and infrequent problem. Among the Level 2 atmospheric profiles, only about 300,299 (48.67% of total Level 1b) good quality profiles contained useful data that passed the quality control (QC) indicated by the quality flag. The unconventional data organization of combining Level 1b (e.g., excess phase, SNR) and Level 2 (e.g., bending angle and refractivity) into a single file per occultation introduces unnecessary complexity to preprocess, interpret and analyze the data.

The Level 2 ionospheric data product includes total electron content (TEC) measurements from the POD antenna, podTEC (positive elevation angles) and occTEC (negative elevation angles). The podTEC is the calibrated (absolute) slant TEC measurement. The elevation of these observables range between 90° (zenith) down to about -20° below the horizon for the GeoOptics satellites. The occTEC is a relative (uncalibrated) TEC estimated from L1 and L2 carrier phases which are tracked with an open loop Radio Occultation receiver and are saved at 1Hz time resolution. The occTEC data product provides relative TEC along ionospheric occultation paths covering the elevation ranges (primarily) between -11° and -18°, corresponding to occultation heights between 370 km to 140 km, respectively. The measurements terminated much higher than what is claimed (i.e., 60 km) in the Data Product Guide (GeoOptics, 2023b).

Overall, there is a large day-to-day variation of valid GeoOptics RO profiles. There are several large dips in profile numbers (e.g., in Oct 2020) for all three RO satellites during the evaluation period. A large portion (~40%) of Level 1b (e.g., excess phase) data failed to generate Level 2 (e.g., atmospheric bending angle, refractivity and ionospheric podTEC & occTEC) data.

GeoOptics data provides global coverage across all latitudes, with higher sampling density in mid- and high-latitude regions due to its high-inclination orbits (98°). This complements the COSMIC-2 constellation's low-inclination orbits, enhancing overall data distribution. Since GeoOptics satellites follow a sun-synchronous orbit, the provided RO data has limited local time coverage, primarily clustering around 11:00 and 23:00 local solar time. This sampling characteristic may raise concerns when using GeoOptics data in climate studies, particularly if diurnal variability is significant.

2. Evaluation Process and Criteria

NASA ESD selected six principal investigators to perform the GeoOptics utility evaluation. CSDA funded an additional separate effort to perform a quality assessment of the GeoOptics data (all teams are listed in Appendix A). The quality assessment is reported in a separate document.

Five of the seven evaluations involved neutral atmosphere data, and two investigators looked at their ionosphere data products. Within these broad categorizations, section 3 of this report details some of the NASA research performed with these GeoOptics data products. The evaluation Principal Investigators (PIs) were required to provide interim, midterm, and final surveys and reporting, and to attend monthly discussions to ensure they had sufficient information and data access to complete their evaluations.

2.1 Evaluation Criteria

The CSDA program provided evaluators the following categories for reporting on their findings for both the quality and utility of the data.

A. *Access, Metadata and Support*
   I. Accessibility of vendor supplied data
      The ease and efficiency with which data can be searched, discovered, and downloaded from vendor systems.
   II. Accuracy and completeness of metadata
      The accuracy and completeness of metadata that accompanies the imagery and data provided by the vendor.
   III. Quality of support services, including documentation
      The availability, responsiveness, and technical expertise required to answer PI inquiries.

B. *Usefulness of the data for advancing Earth system science Research and Applications*
   The ability of vendor-supplied data to support Earth system science Research and Applications.

C. *Quality of Vendor Supplied data*
   The quality of data attributes, such as radiometric calibration, geolocation accuracy, and platform intercalibration.

2.2 Program Activities

The evaluation was facilitated by conducting periodic reviews and surveys, PI all-hands, monthly technical interchange meetings. The evaluation timeline is depicted in Figure 1.

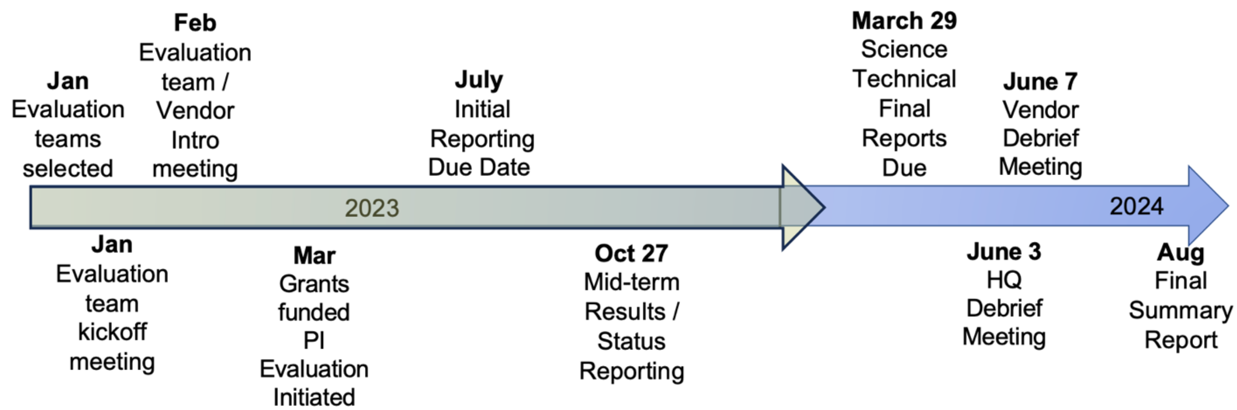

Figure 1. Timeline of Evaluation activities since awarding the purchase agreement.

2.3 Meetings, Periodic Reviews and Surveys

In addition to the team and vendor kick-off meetings, evaluation PIs were required to participate in periodic reviews and report on the usefulness of the data and current research progress. The PIs were asked to submit quad charts at three points during the evaluation, the first one shortly after gaining access to the data, the second at the evaluation midpoint, and lastly as part of their final submission. An in-person midterm meeting was held at the Goddard Space Flight Center which allowed the PIs to share their preliminary results and exchange information. All reports and surveys were synthesized in the creation of this final summary report.

2.4 Monthly Technical Interchange Meetings

Monthly conference calls were set up to facilitate technical interchange among the PIs and with CSDA staff to help identify and resolve issues related to data access, quality, completeness, and processing. The PIs were asked to identify issues and share information that might be relevant to other PIs. The conference calls were set up as a means by which to ensure timely identification and prompt resolution of issues that might arise. These meetings also allowed the CSDA staff an opportunity to gather and relay any concerns that the team may have to the vendor to accelerate resolution of any potential problems.

2.5 Community Engagement and Feedback

As the capabilities and numbers of commercial vendors grow, it is important to continuously monitor the development of new commercial technology, acquire relevant data to complement existing and future missions, and evaluate these data over time. The CSDA team continues to provide status updates, answer questions about data and data access, and provide information about future procurement opportunities for other constellation providers at various science conferences and workshops throughout the year. The community engagement serves as an open forum for dialogue between experts across the science data research stratum and helps to showcase NASA's progress and commitment to building stronger bonds with the commercial sector.

3. Key Findings

The evaluation was focused on assessing the utility of GeoOptics data for advancing three of NASA's six Earth Science focus areas: Atmospheric Composition, Weather and Atmospheric Dynamics, and Climate Variability and Change. A summary of the research areas represented by the GeoOptics evaluation PIs is presented in Figure 2.

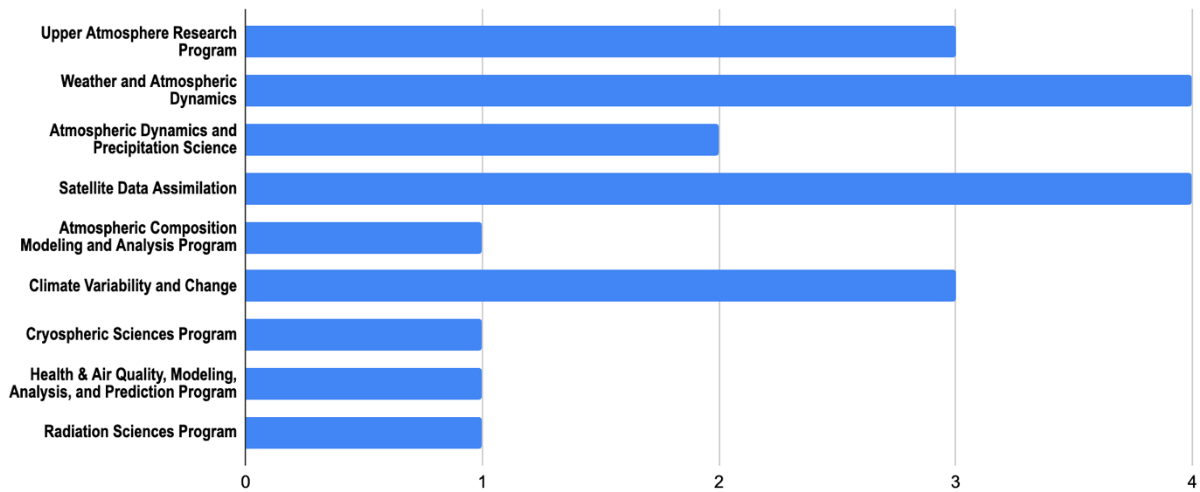

Figure 2. The figure represents the number of evaluation teams involved with different NASA research areas; most evaluations covered more than one research area.

The GeoOptics data evaluated were acquired through the U.S. Government End User License Agreement (EULA) and were available only to the science team during the period of the evaluation. Following the evaluation period, the data were made available to U.S. Government-funded researchers through the CSDA Satellite Data Explorer (SDX). The GeoOptics data evaluated are shown in Table 1, with evaluation criteria outlined in section 2.1. The key findings address the objectives of the evaluation and are described in the following sections.

3.1 Data Access, Customer Support, and Metadata

Over the period from January 1, 2020, to April 30, 2021, GeoOptics provided data across all levels, including Levels 0, 1a/1b, and 2, that provided the evaluation teams with comprehensive resources for analysis.

3.1.1 Data Access

All the data can be easily accessed and downloaded from the Amazon Web Services (AWS) with detailed and well-organized access guides provided by GeoOptics. However, it is worth noting the ionosphere data product exhibited some data quality issues at the beginning of the evaluation process. It took three separate deliveries over 4 months of time before usable data became available. The first delivery was on May 18th, 2023. The second was on August 7th, 2023. The third was September 29th, 2023. However, the GeoOptics team was attentive and responsive to all PI questions.

3.1.2 Documentation and Metadata

The vendor provided two major documents, a data product guide (GeoOptics, 2023b) and the detailed data processing description (GeoOptics, 2023a). In addition, the User Guide for Level 2 temperature and humidity retrieval data products derived from the One-Dimensional Variational (1DVar) assimilation technique (GeoOptics, 2023c) was also included.

GeoOptics provided detailed documentation on metadata, GeoOptics instrument characteristics, their data processing methods, and data products, which aided in the ability of the evaluation teams to validate findings. Overall, the metadata in Level 1a, Level 1b, and Level 2 data products were found to adequately support the quality evaluation tasks.

However, there were also some metadata issues noted. GeoOptics does not provide Level 1b ancillary data containing the navigation bit stream, which is necessary for re-processing or post-processing the accumulated phase data, preventing independent verification of the data. In contrast, data centers such as the UCAR- COSMIC Data Analysis and Archive Center (CDAAC) and GFZ Potsdam, offer a Level 1b data product, gpsBit, which can be used alongside opnGns to remove the navigation bits from the accumulated phase.

There are inconsistencies in the signal-to-noise ratio (SNR) values between the GeoOptics and UCAR-CDAAC framework calculations, and incorrect starting time attributes in the Level 1b data. These anomalies raised concerns about data stability, particularly with Level 2 data, and prompted questions about the need for improved quality control. In addition, in the Level 2 refractivity data product, the azimuth angle of the occultation plane is missing, there are negative minimum heights of RO refractivity profiles (~80%), and some obvious longitude/latitude errors. These are relatively small issues that can be easily fixed and do not impact the overall usage of the data product, however, an improved quality control process by the vendor is recommended.

BUFR (Binary Universal Form for the Representation of meteorological data) is the standard WMO (World Meteorological Organization) format for distributing weather observations (including RO data) operationally. The GeoOptics Level 2 BUFR files lack the local RO ray azimuthal angle metadata, which means that some 2D forward operators (e.g., the European Centre Medium-Range Weather Forecast [ECMWF] model) may be unable to assimilate these files "out of the box". However, the azimuthal angle could be inferred from the latitude/longitude of adjacent observations in the same profile. In addition, the vertical sampling of the BUFR data is provided at a higher vertical resolution (~500 - 600 levels), which far exceeds the conventional standard of 247 levels for data assimilation. Therefore, data thinning, through smoothing and resampling, is needed to make the data compatible for data assimilation purposes. Furthermore, the time parameter provided in occTEC and podTEC as "seconds" should be "GPS seconds", to be consistent with the data guide documentation.

3.1.3 User Support

Overall, the GeoOptics team provided responsive and supportive assistance for users with questions about the data products. The GeoOptics team was ready to clarify technical details and helped users navigate the data effectively.

During the evaluation process, the team identified multiple issues impacting the reliability of the GeoOptics data. Notable data anomalies, such as spikes and data gaps in refractivity and temperature/humidity profiles, underscored the need for continuous vendor support to address these inconsistencies. Despite these challenges, the vendor's prompt and effective support significantly enhanced the user experience, facilitating successful GeoOptics data evaluation processes.

3.2 Data Utility for NASA Science

The utility assessment of GeoOptics GNSS Radio Occultation data was primarily focused around two major Earth science focus areas: weather and climate and included both the neutral atmosphere and the ionosphere data products.

The CSDA GeoOptics evaluation team can be separated into two groups, those focusing on neutral atmosphere science applications (5 PIs) and the those with ionosphere science applications (2 PIs). The distribution of the scientific utility of the GeoOptics data from the evaluation team is summarized in Figure 3 below.

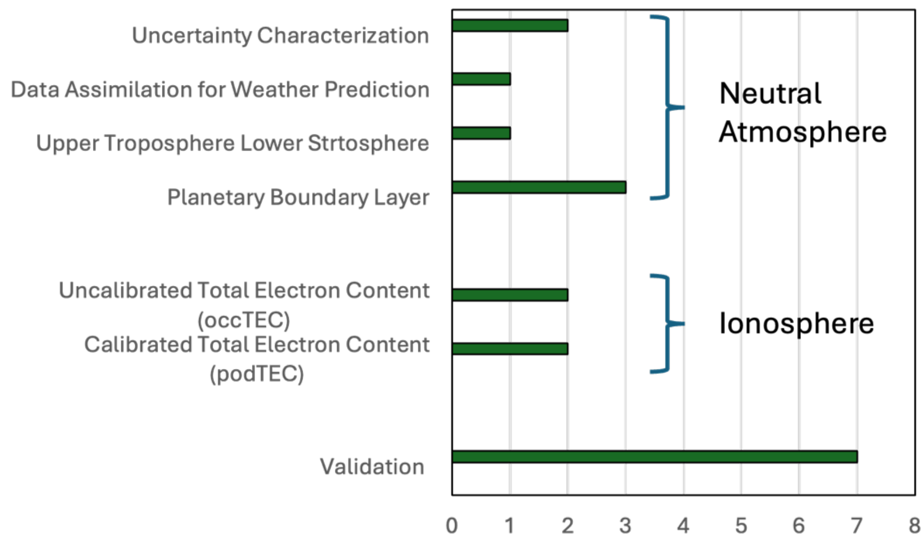

Figure 3. The different GeoOptics products and types of data evaluated, where the x-axis is the number of PI teams. Some teams evaluated multiple products and types.

3.2.1 GeoOptics Processing Algorithm and Data Quality Evaluation

3.2.1.1 GeoOptics vs. UCAR-CDAAC Processing Algorithm

The Level 2 data from the vendor (i.e., GeoOptics-processed) exhibit a substantial day-to-day variation in data volume. Unexpected disparities among the three GeoOptics satellites were also noted. Furthermore, the retrieved raw bending angle data exhibits significant noise, rendering these data challenging to use for RO applications. Additionally, in comparison with the co-located ECMWF short-term forecast analysis, increasing refractivity errors above 20 km highlight the limitations in the bending angle optimization method employed during processing. All these indicate potential limitations of the GeoOptics processing algorithm.

Therefore, to comprehensively evaluate the GeoOptics data quality and its utility, one of the PI teams directly processed the vendor-provided Level 1a data to produce Level 1b and Level 2 data by using the UCAR-CDAAC framework.

The penetration depth, which is defined as the minimum altitude above ground level (AGL) with valid bending angle/refractivity retrieval for a given RO event, serves as a crucial metric for evaluating the efficiency of RO retrievals in the lower troposphere. Within the UCAR-CDAAC data processing system, the minimum altitude of an RO profile is determined by truncating the data below 1.5 times the RO background noise, effectively detecting significant signal amplitude drop-off, due to tracking errors, while retaining valuable information at depth.

In the GeoOptics-processed data, globally, about 58% of RO data penetrates to 1 km AGL, with only 31% reaching down to 1 km in tropical regions. Such low percentage of high-quality data in the lower troposphere hinders the study of the planetary boundary layer (PBL) due to insufficient samples.

In contrast, in the independent CDAAC-processed GeoOptics data, the performance of penetration depth improves significantly. Globally, 82% of RO data penetrates to 1 km, with 75% reaching down to 1 km in the tropical regions. The CDAAC-processed RO data exhibit significantly improved quality, deeper penetration into the lower troposphere especially over the ocean, and better temporal consistency. While still fewer GeoOptics ROs meet the quality control (QC) criteria compared to ROs from other missions (such as COSMIC-2), those that do pass the QC check, demonstrate reasonable retrievals that are comparable to other RO missions. This indicates that improvement in the GeoOptics RO data processing algorithm is needed to maximize the scientific value of the RO data applications.

Considering the differences in processing, the following sections address the scientific utility of both GeoOptics-processed RO data as well as the CDAAC-processed RO data.

3.2.1.2 Uncertainty Evaluation of GeoOptics Level 2 Bending Angle/Refractivity Data

Estimation of the error characteristics of observational data sets is important for their scientific applications for weather and climate studies. Estimates of the uncertainty of observations are necessary components of their assimilation into weather models. The three-cornered hat (3CH) (Sjoberg et al. 2021) method has been applied to assess the GeoOptics RO bending angle and refractivity observation uncertainties, with the aid of Global reanalysis and multiple other RO missions (e.g., BUFR data from COSMIC-2 and Spire). The uncertainty of GeoOptics BUFR data processed by both GeoOptics and UCAR-CDAAC were analyzed separately.

The GeoOptics-processed RO data yields ~30% fewer quality profiles compared to CDAAC-processed data. Vertical filtering adjustments at specific levels cause abrupt, unphysical shifts in uncertainty and outlier statistics. It is worth noting that vendor's 2021 processing update reduced bending angle uncertainty below 40 km, which is promising.

On the other hand, the CDAAC-processed GeoOptics data shows broad agreement with the COSMIC-2 data, confirming the high scientific value of GeoOptics Level 2 bending angle and refractivity data. In comparison with COSMIC-2, the CDAAC-processed GeoOptics data show slightly larger uncertainty with more outliers. but are reliable for use in data assimilation systems, with comparable quality to COSMIC-2 mission data. These CDAAC-processed GeoOptics data are highly valuable for global weather and climate research.

3.2.2 Neutral Atmosphere Applications

Five PIs focused on the science utility of the neutral atmosphere data product across multiple levels of processing steps (Level 1a, 1b, & 2). The GNSS radio occultation (RO) technique offers self-calibrated, highly stable, high vertical resolution (~100 m in lower troposphere), global sounding measurements in all-weather conditions, which make it ideal for global planetary boundary layer, tropopause studies in the upper troposphere and lower stratosphere (UTLS), as well as potential improvement of numerical weather predication (NWP) models for severe weather through data assimilation.

3.2.2.1 Planetary Boundary Layer Height Climatology

In the GeoOptics-processed Level 2 refractivity data, the mean penetration depth of all the QC profiles and the fractional profiles penetrating below 500 m shows high spatial variation across the globe. The penetration depths over the mid and high latitudes are below 1.5 km. However, over the tropical region (20 S – 20 N), the mean penetration depths are in the 4 – 6 km range, with only 5 – 20 % that reach below 2 km, and few RO profiles reaching below 500 m (<1 % within 15 S – 15 N). In the southern hemisphere mid- and high-latitudes, over 75% of the profiles reach below 2 km. More variation is seen in the northern hemisphere due to more terrain variation. Such poor penetration depths over most of the tropical region significantly limits the application for PBL studies over the tropics.

The GeoOptics-processed refractivity data were used to analyze the PBL height over the U.S. Southern Great Plains (SGP) and over the Arctic Ocean. Over the SGP, despite a rather low percentage of high-quality PBL profiles due to penetration issue, the GeoOptics PBL refractivity profiles show reasonable agreement with radiosondes. Over the Arctic Ocean, GeoOptics profiles exhibit much deeper penetration, with up to 60% reaching the surface, highlighting their potential as a valuable resource for polar PBL studies. However, limited spatial coverage resulted in noisy PBL height estimates in this region.

GeoOptics-processed bending angle and refractivity data generally lack sufficient penetration depth for PBL studies, especially in the tropics, while CDAAC-processed data achieve much deeper penetration into the PBL, with quality comparable to COSMIC-2 measurements.

The global PBL height climatology derived from the CDAAC-processed GeoOptics Level 2 data show spatial and seasonal variability consistent with COSMIC data (e.g., Ao et al., 2012), further validating the robustness of the observed spatial patterns of PBL height derived from GeoOptics data.

3.2.2.2 Upper Troposphere and Lower Stratosphere (UTLS) Climate Applications

Like other GNSS RO missions (e.g., COSMIC-2), the GeoOptics-processed data provide high-quality bending angle and refractivity measurements between approximately 5 km and 35 km altitude, making them highly valuable for UTLS scientific studies. However, temporal and satellite-dependent variations in data quality introduce some uncertainty for UTLS applications. In contrast, the CDAAC-processed GeoOptics Level 2 data exhibit quality more comparable to COSMIC-2, thereby increasing their utility for scientific research.

Based on the CDAAC-processed GeoOptics Level 2 refractivity data, both cold-point tropopause (CPT) and WMO lapse-rate tropopause (LRT) (WMO, 1957) were derived from the retrieved dry temperature profiles. In the tropics, the tropopause is predominantly located at 16-17 km, with lowest temperature about 190 K. In midlatitudes, the tropopause height drops rapidly with latitude, to around 8 km near +/-60° along with an increase of tropopause temperature. Over the polar regions, the behaviors of thermal tropopause vary between winter and summer poles, which is believed to be caused by the stratospheric polar vortex which is colder in the southern hemisphere than in the northern hemisphere.

The study indicates that CDAAC-processed GeoOptics RO is suitable for examining the fine structures and seasonal variabilities of the tropopause. The revealed features align well with those observed in other datasets (Son et al., 2011). In addition, good agreement between CDAAC-processed GeoOptics and COSMIC-2 bending angle variations associated with the quasi-biennial oscillation in the stratosphere further demonstrates the value of the GeoOptics data.

3.2.2.3 Data Assimilation for Numeric Weather Prediction

To assess the suitability of GeoOptics Level 2 bending angle data for assimilation in numerical weather prediction (NWP) models, the data were assimilated in the NOAA's Hurricane Weather Research and Forecasting (HWRF) Gridpoint Statistical Interpolation (GSI) mesoscale data assimilation system for the analyses and forecasts of Hurricane Hanna (2020).

Hurricane Hanna developed off the Gulf Coast of the U.S. on July 22, 2020. The storm intensified under mostly favorable environmental conditions to a category 1 hurricane before striking the southern Texas coast; many operational models, including the HWRF, were late in catching on to the high rate of Hanna's intensification.

GeoOptics-processed Level 2 BUFR files contain all RO bending angle data and metadata needed for assimilation in weather forecasting models using a one-dimensional forward operator. GeoOptics bending angles could provide useful water vapor and temperature information for hurricane model analyses in the tropical lower troposphere.

However, due to their higher native vertical resolution compared to the standard configuration (e.g., 247 levels) used by UCAR and the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT), the GeoOptics bending angle profiles cannot be directly appended to National Centers for Environmental Prediction (NCEP) RO data BUFR files without either thinning them first or modifying the NCEP BUFR-processing library source codes.

According to the vendor, applying less vertical smoothing and thinning compared to UCAR's and EUMETSAT's bending angle processing protocols, was based on internal discussions with NASA's Jet Propulsion Laboratory RO science team concerning the fact that the conventional 247 levels may require excessive smoothing that could adversely impact data assimilation by increasing vertical observation error correlations. The thought being that providing the GeoOptics bending angle BUFR data in higher vertical resolution would allow the evaluators the freedom to determine optimal smoothing for data assimilation applications.

GeoOptics data were successfully assimilated in NOAA's HWRF-GSI mesoscale data assimilation system and demonstrated an impact on the analysis of HWRF water vapor field near the observations. However, the assimilation has a generally neutral impact on the intensity forecasts for Hurricane Hanna in the HWRF model, likely due to the small sample size resulting from limited spatial sampling.

3.2.3 Ionosphere Applications

GNSS Radio Occultation (RO) Total Electron Content (TEC) data were used in space weather applications to monitor and predict ionospheric conditions that impact communication and navigation systems. Specifically, TEC measurements help assess ionospheric electron density variations, which can cause signal delays and scintillations in GNSS signals. These disruptions affect GPS accuracy, satellite communications, and high frequency radio propagation, especially during geomagnetic storms.

The Level 2 ionospheric data product includes TEC measurements from the POD antenna, represented by the podTEC and occTEC measurement files, respectively. The podTEC files contain the calibrated (absolute) slant TEC measurements. The occTEC measurement is a relative (uncalibrated) TEC along ionospheric occultation paths, estimated from the L1 and L2 carrier phase signals which are tracked with an open loop RO receiver and saved at 1 Hz time resolution.

3.2.3.1 Total Electron Content from POD antenna (podTEC)

GeoOptics podTEC data appears to be of high quality for scientific applications involving high-elevation angles (e.g., above 60°) in mapping ionospheric TEC, and it extends coverage into higher latitudes, complementing COSMIC-2 measurements that are primarily limited to low latitudes. There is an approximate 3 TECu (Total Electron Content Unit) positive bias in GeoOptics podTEC data compared to COSMIC-2, which can be attributed to its lower orbits.

However, vertically, the GeoOptics data provides significantly less ionospheric coverage of lower ionosphere layer measurements than COSMIC-2. A relatively low number of podTEC occultation profiles within most of the TEC tracks terminate at -15° which corresponds to the tangent height of about 200 km. This altitude cutoff restricts the quantity of useable occTEC profiles for inversion into ionospheric density profiles, which are not provided by GeoOptics.

3.2.3.2 Total Electron Content from POD antenna (occTEC)

The occTEC data product provides relative TEC along ionospheric occultation paths covering the elevation ranges (primarily) between -11° and -18°, corresponding to occultation heights between 370 km to 140 km, respectively. The measurements terminated much higher than what is claimed (i.e., 60 km) in the documentation (GeoOptics, 2023b). The altitude limitation of the occTEC data reduces its scientific value by excluding the ionospheric (90-150 km), rendering it unsuitable for investigating Sporadic-E events, which are characterized by the sudden, localized formation of dense ionization patches in the E-region.

Most COSMIC-2 profiles extend from the satellite altitude (either 720 or 525 km) down to 100 km or lower, whereas most GeoOptics profiles only reach to a few kilometers below the satellite. Nearly 90% of COSMIC-2 data contains high-value occultation measurements, compared to only 42% for GeoOptics. While over half (58.11%) of COSMIC-2 occultations extend to altitude of 100 km or higher, only 2.52% GeoOptics occultation data achieve comparable depth.

The electron density profiles (EDPs) can be derived from the low elevation occTEC data through Abel inversion (e.g., Yue et al., 2010). Although the quality of Abel-inverted profiles from the GeoOptics data is high compared to the ionosonde data, the limited low-elevation TEC measurements severely limit the number of podTEC measurements that are suitable for retrieving EDPs. Therefore, the number of profiles produced from the GeoOptics data is several orders of magnitude lower than for COSMIC-2 over the same time range.

3.3 Data Quality

The quality of GeoOptics GNSS data product has been evaluated by researchers with expertise in GNSS Radio Occultation analysis to assess if the quality of the GeoOptics data are suitable for scientific research.

A quality assessment was performed using a set of quality assessment guidelines, similar to those used for past CSDA investigations, but adapted for GNSS radio occultation data by NASA subject matter experts. The matrices in Figure 4 show our initial quality assessment of these products using these new guidelines.

The rationale used to grade each box were generated, as best as possible, using input from the CSDA investigations. We expect the initial set of data quality guidelines to undergo review and may be updated, based on further discussions. However, we do not expect any changes to the guidelines to affect the overall assessment of the GeoOptics data for NASA science and applications.

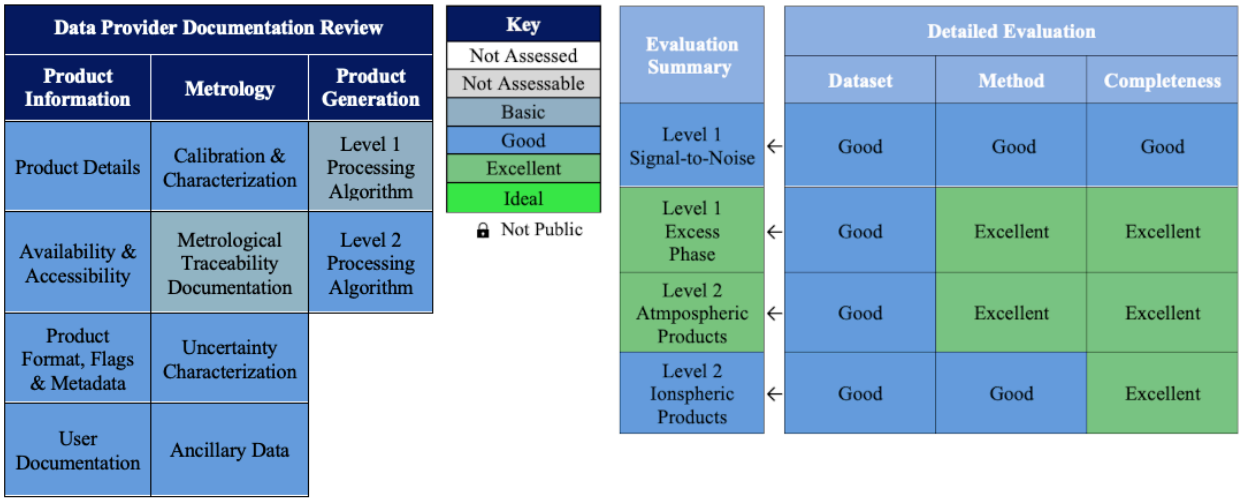

Figure 4. Summary quality assessment matrices for GeoOptics data products.

4. Summary and Recommendations

NASA-funded investigators were able to evaluate all levels of GeoOptics data product except the Level 0 data. All the evaluation PIs indicated that the GeoOptics data were suitable for continued scientific use for NASA research involving neutral atmosphere and ionosphere data and recommended continuing access to all levels of GeoOptics data products currently offered by the vendor. However, the PIs noted a few key points for improvement.

The current Level 1a data products demonstrated a high quality of scientific value for neutral atmosphere science applications spanning multiple thematic areas (UTLS, PBL, data assimilation etc.). However, the current GeoOptics Level 2 data products offer limited value for PBL studies and requires processing algorithm improvement, especially for study of the lower troposphere. On the other hand, the podTEC and occTEC products both demonstrate high quality slant TEC measurement at high elevation angles. The early termination of the low-elevation TEC measurements severely limits their scientific value for studying ionosphere E-region (90-150 km) and Sporadic-E events. The 200 km cutoff restricts the quantity of useable occTEC profiles for inversion into ionospheric density profiles, which are not provided by GeoOptics.

Recommendations:

- Enhance the Level 1b data processing algorithms, especially for the neutral atmosphere data processing – particularly for the lower troposphere – to enhance PBL studies.
- Enhance future instrument capabilities to capture low-elevation ionospheric measurement to strengthen ionospheric research.
- Ensure uniformity in Level 2 processing of all GeoOptics data using the same version of algorithms consistently.

- Improve metadata description and provide detailed quality control and documentation.
- Improve local time sampling by deploying future constellations in non-sun-synchronous polar orbits.

5. Conclusion

Over the span of a year, RO investigators representing NASA research and analysis science focus areas (see Figure 2), evaluated GNSS radio occultation data from GeoOptics. A significant majority of these evaluations demonstrated the usefulness of these commercial data for advancing scientific research and applications. However, the evaluation teams encountered numerous limitations that diminished the utility of some aspects of the data (e.g., limited vertical range sampling), and/or increased the effort needed to preprocess, interpret and analyze the data (e.g., unconventional data organization, and documentation and metadata issues, etc.). Overall, the utility of the evaluated data, in addition to their polar coverage, outweighed the difficulties encountered, and it was determined that the GeoOptics GNSS Radio Occultation data would complement NASA and other existing RO satellite system capabilities.

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Appendix A. Listing of Evaluation Research Projects

Principal Investigator	Investigation Title
Neutral Atmosphere	
Feiqin Xie Texas A&M University, Corpus Christi	Evaluation of the GNSS radio occultation sounding of neutral atmosphere from GeoOptics CICERO constellation
Xi Shao University of Maryland	Evaluation of GeoOptics Level 1 and Level 2 Atmospheric Data Quality
Jeremiah Sjoberg University Corporation for Atmospheric Research	Uncertainty evaluation of GeoOptics GNSS radio occultation bending angle and refractivity using the three-cornered hat method
Zhen Zeng University Corporation for Atmospheric Research	Data Processing and Scientific Evaluation of GeoOptics GNSS Radio Occultation Data for the NASA CSDA Program
Manisha Ganeshan NASA GSFC	Evaluating the Planetary Boundary Layer Height derived from GeoOptics GNSS RO Measurements
Ionosphere	
Joseph Hughes OrionSpace	Evaluating the Tropospheric and Ionospheric GeoOptics RO data
Sebastijan Mrak University of Colorado	GeoOptics GNSS Data for Space Weather and Beyond
Quality Assessment	
Dong Wu NASA GSFC	GeoOptics Data Quality Assessment