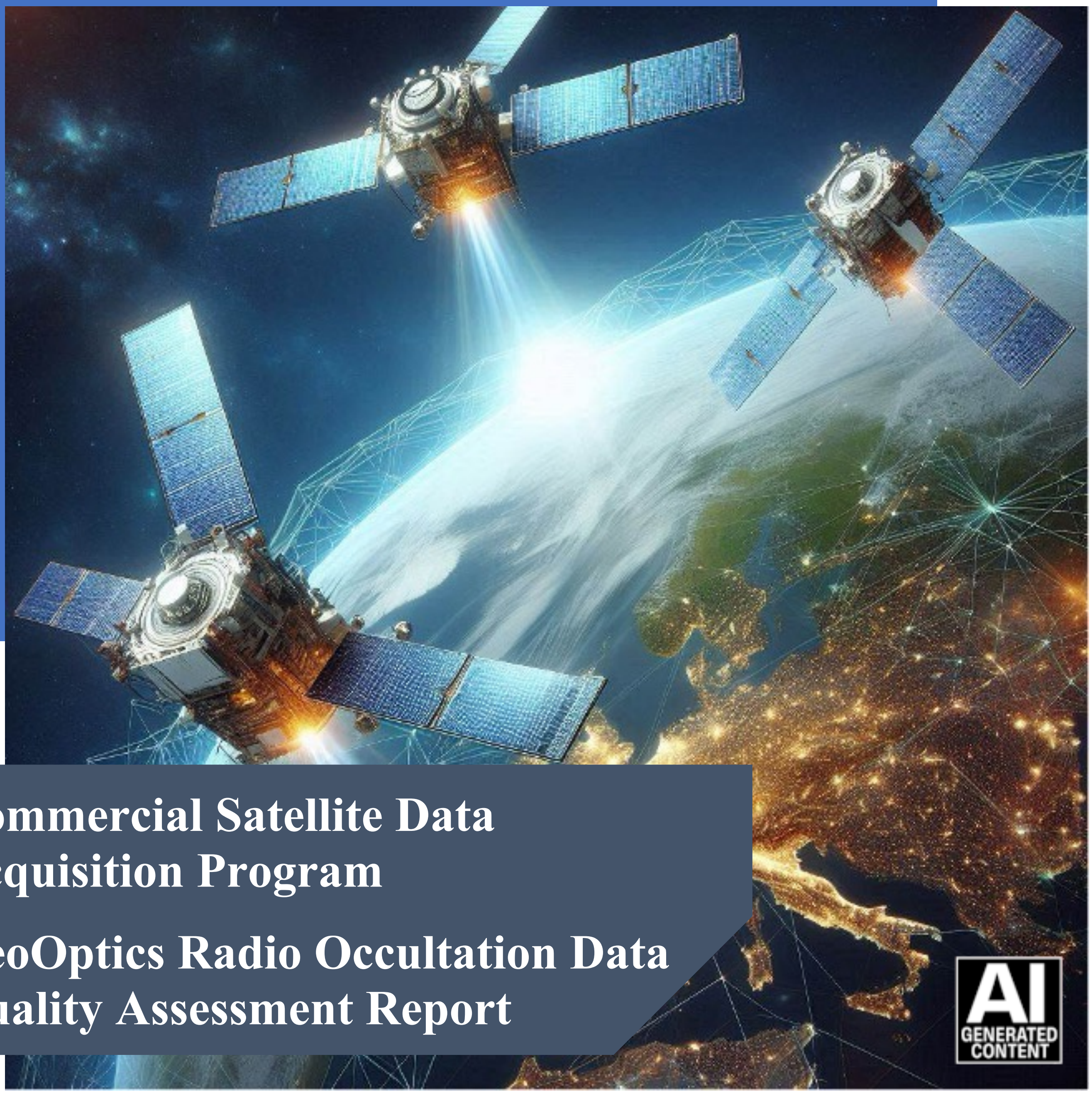

Commercial Satellite Data Acquisition Program

GeoOptics Radio Occultation Data Quality Assessment Report

Goddard Space Flight Center
Greenbelt, MD

GeoOptics Radio Occultation Data Quality Assessment Report

Signature/Approval Page

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Preface

This document is under CSDA Project configuration control. Once this document is approved, CSDA approved changes are handled in accordance with Class I and Class II change control requirements described in the CSDA Configuration Management Procedures based on NASA standard configuration practices, and changes to this document shall be made by document change notice (DCN), documented in the Change History Log or by complete revision.

Abstract

The evaluation summarized in this report was conducted by subject matter experts funded by NASA's Commercial Satellite Data Acquisition (CSDA) Program. The purpose of the evaluation is to determine the utility of the GeoOptics data quality for the NASA Earth science research and applications community. The results of the evaluation help to inform NASA program management on the quality of the data for 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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Acronyms & Abbreviations

1DVAR	1-Dimensional Variation method
ATBD	Algorithm Theoretical Basis Document
BUFR	Buffer file format
CF	Climate & Forecast (Metadata Convention)
CDAAC	COSMIC Data Analysis and Archive Center
CEOS	Committee on Earth Observation Satellites
CICERO	Community Initiative for Cellular Earth Remote Observation
cicPod	LEO POD data, includes orbits and clock biases
cicPrf	GeoOptics Level-2 file name (bending angle and refractivity)
COSMIC	Constellation Observing System for Meteorology Ionosophere and Climate
CSDA	Commercial Satellite Data Acquisition
DCB	Differential Code Bias
DOI	Digital Object Identifier
ECEF	Earth-centered, Earth-fixed
ECI	Earth-centered inertial
ECMWF	European Centre for Medium-Range Weather Forecasts
EDAP	Earthnet Data Assessment Pilot
EO	Earth Observation
ERA5	ECMWF ReAnalysis Model 5
ESA	European Space Agency
EULA	End-User License Agreement
FAIR	Findable, Accessible, Interoperable and Reusable
F_2-layer	The highest permanently observable layer of the ionosphere
FM-85, -87	Flight model 85, 87
FRM	Fiducial Reference Measurement
GLONASS	Russian Global Navigation Satellite System
GNSS	Global Navigation Satellite Systems
GPS	Global Positioning System
GUM	Guide to the Expression of Uncertainty in Measurement
IGS	International GNSS Service
INSPIRE	Infrastructure for Spatial Information in Europe
L1	L Band 1, GPS L1 signal
L2	L Band 2, GPS L2 signal
LEO	Low Earth Orbit
NASA	National Aeronautics and Space Administration
NetCDF4	Network Common Data Format, version 4
NOAA	National Oceanic and Atmospheric Administration
NPL	National Physical Laboratory, UK
occTEC	GeoOptics Level-1B file name from occultation antenna

ogngns	GeoOptics Level-1A occultation file name
podTEC	GeoOptics Level-1B file name from POD antenna
PBL	Planetary Boundary Layer
POD	Precise Orbit Determination
PUG	Product User Guide
PUM	Product User Manual
QA	Quality Assessment
QA4EO	Quality Assurance Framework for Earth Observation
QA4ECV	Quality Assurance Framework for Essential Climate Variables
RINEX	Receiver Independent Exchange
RO	Radio Occultation
SI	Système International (International System of Units)
SNR	Signal-to-Noise Ratio
SP3	Standard Product #3 file format
TEC	Total Electron Content
UCAR	University Corporation for Atmospheric Research
URL	Universal Resource Locator
UTC	Universal Time Code

Executive Summary

The Commercial Satellite Data Acquisition (CSDA) Program was established to identify, evaluate, and acquire data from commercial sources that support National Aeronautics and Space Administration (NASA) Earth science research and application goals. NASA's Earth Science Division (ESD) recognizes the potential impact commercial small-satellite (Satellite) constellations may have in encouraging/enabling efficient approaches to advancing Earth System Science and applications development for societal benefit. Commercially acquired data may also provide a cost-effective means to augment and/or complement the suite of Earth observations acquired by NASA and other U.S. government agencies and those by international partners and agencies.

In this report, CSDA provides an evaluation of the quality of data provided the GeoOptics satellite constellation for advancing NASA's Earth system science research and applications. The quality of the GeoOptics Radio Occultation (RO) products was evaluated using input from the CSDA Program's GeoOptics data evaluation team selected by NASA and a NASA subject matter expert enlisted to evaluate the fundamental quality of the data. This assessment was completed in accordance with a recently developed draft of the Global Navigation Satellite Systems (GNSS)-RO Data Quality Assessment (QA) Guidelines. The QA lead assessed the fundamental quality of the GeoOptics data using results from the CSDA evaluation. Details about the utility of the GeoOptics data for NASA science are available in a separate CSDA Program Evaluation Report. This quality assessment reflects the current understanding of the GeoOptics constellation and reported measurements. Additional relevant input as well as changes to the technology could necessitate updates to this assessment.

At the time of the evaluation, GeoOptics no longer had any remaining satellites in orbit. Their first two were launched in November of 2018, and a third was launched in December of that year. One of the first two failed in April of 2019, after just 4 months. A fourth was launched in September of 2020, and there were three satellites in operation for 10 months. In June of 2021, two deorbited, leaving just one in operation, which ended in January of 2022. The NASA evaluation team had already been selected at this time. The GeoOptics satellites and their lifetime in orbit are shown below in Figure 1, the black box in the figure indicates the time period of the CSDA purchase for evaluation.

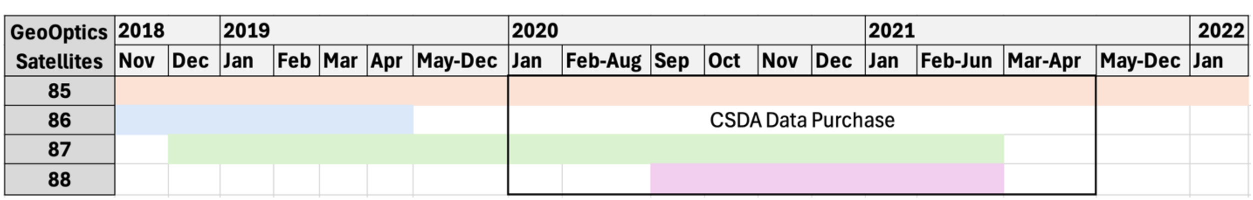

Figure 1. The GeoOptics constellation lifetime and the data purchased by CSDA.

GeoOptics CICERO (Community Initiative for Cellular Earth Remote Observation) is a constellation of micro-satellites designed to make Global Positioning System (GPS) and GNSS-RO observations of Earth's atmosphere. Initially, GeoOptics developed the CICERO 115 kg microsatellites together with the University of Colorado Laboratory for Atmospheric and Space Physics (LASP) using the same receiver developed for the Constellation Observing System for Meteorology, Ionosphere, and Climate-2 (COSMIC-2) mission. Later, the GNSS-RO receiver payload, called Cion, was minimized to fit a smaller 6U CubeSat. The data delivered to CSDA are from the Cion receivers on CICERO 85, 87 and 88 satellites.

Table 1. The GeoOptics products and data levels.

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 (cicPrf, cicPOD)
Level 2 (Atmospheric Data)	Bending angle, refractivity, dry pressure and dry temperature (cicPrf)
	Water vapor, temperature and pressure (1D-Var)
	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 delivered but not evaluated.

The evaluation found that the GeoOptics-processed RO data are scientifically useful for data assimilation and other atmospheric (e.g., bending angle, temperature) and ionospheric (e.g., total electron density) science applications. Compared to COSMIC-2, GeoOptics data have significantly lower signal-to-noise ratio (SNR). The excess phase data need better quality control (QC) to produce good bending angle profiles. GeoOptics-processed bending angle may be biased with additional uncertainties from antenna characteristics, clock errors, and attitude/positioning errors. The GeoOptics Level-2 occTEC product was not found to be very useful for meaningful scientific applications, due to its limited vertical coverage.

Further improvements could be made in data documentation, metadata, as well as the data quality stability.

1. Evaluation Maturity Matrices

1.1 Summary Product Maturity Matrix

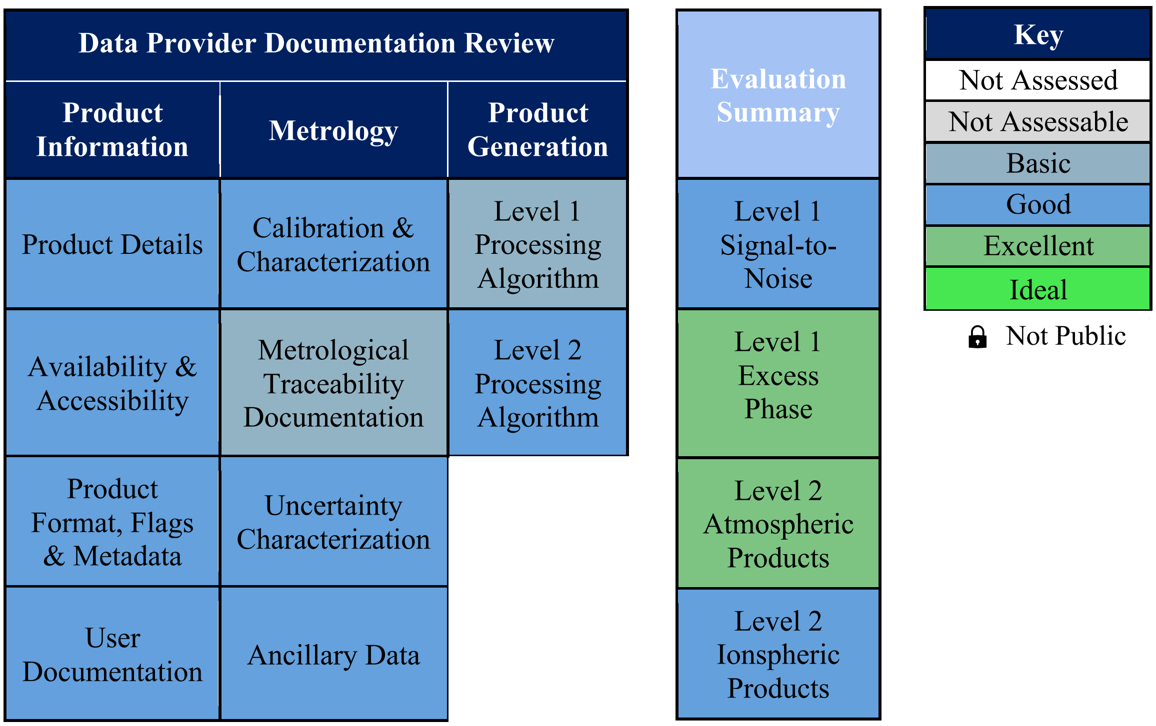

Figure 2. Summary Product Evaluation Matrix

1.2 Detailed Evaluation Maturity Matrix

Evaluation Summary	Detailed Evaluation		
	Dataset	Method	Completeness
Level 1 Signal-to-Noise	Good	Good	Good
Level 1 Excess Phase	Good	Excellent	Excellent
Level 2 Atmospheric Products	Good	Excellent	Excellent
Level 2 Ionspheric Products	Good	Good	Excellent

Key
Not Assessed
Not Assessable
Basic
Good
Excellent
Ideal
Not Public

Figure 3. Detailed Evaluation Maturity Matrix for the RO domain, showing the Assessment Summary column from the Summary Evaluation Matrix

2. Data Provider Documentation Review

2.1 Product Information

<table>
<tr><th colspan="2">Product Details</th></tr>
<tr><td colspan="2">Grade: Good</td></tr>
<tr><td>Justification</td><td>Most of the variable information and ancillary parameters are documented in the product file and user data guide. The user documentation appears to be clear and helpful.
Additional comments about information missing in the data products are included in section 3.2.</td></tr>
<tr><td>Product Name</td><td>opnGns, cicPOD, cicPrf</td></tr>
<tr><td>Sensor Name</td><td>Cion receiver</td></tr>
<tr><td>Sensor Type</td><td>GNSS receiver for radio occultation (RO) and POD</td></tr>
<tr><td>Mission Type</td><td>Radio Occultation</td></tr>
<tr><td>Mission Orbit</td><td>Polar</td></tr>
<tr><td>Product Version Number</td><td>V01. Note that a new version of cicPrf (Level-2), with a change to the data flags was released during the evaluation (not evaluated)</td></tr>
<tr><td>Product ID</td><td>NA</td></tr>
<tr><td>Processing level of product</td><td>Level-1(opnGns, cicPOD)
Level-2 (cicPrf)</td></tr>
<tr><td>Measured Quantity Name</td><td>Calibrated excess phase
Signal-to-noise ratio
Atmospheric bending angle
Refractivity
Temperature
Water vapor
Ionospheric total electron content</td></tr>
<tr><td>Measured Quantity Units</td><td><table>
<tr><td>Calibrated excess phase</td><td>meters</td></tr>
<tr><td>Signal-to-noise ratio</td><td>unitless</td></tr>
<tr><td>Atmospheric bending angle</td><td>radians</td></tr>
<tr><td>Refractivity</td><td>N-units</td></tr>
<tr><td>Temperature</td><td>K</td></tr>
<tr><td>Water vapor</td><td>g/kg</td></tr>
<tr><td>Ionospheric total electron content</td><td>TECU = TEC Unit, where 1 TECU = 10^{16} electrons/m²</td></tr>
</table></td></tr>
</table>

Spatial Coverage	Global
Vertical resolution	200 m
Temporal resolution	1200 - 1500 profiles per day
Temporal coverage	Most profiles provided at two local times
Point of Contact	Alex Saltman <alex@geooptics.com>
Product locator (DOI/URL)	N/A
Conditions for access and use	U.S. Government-Funded Researchers

Availability & Accessibility	
Grade: Good	
Justification	Data were made available via an Amazon S3 bucket. The organization within the S3 bucket is as follows: data type/satellite/year. Filenames contain some metadata such as date and time, and the files themselves contain attributes that can be used to filter and search the data. Some products are organized differently between the standard Level-1 and Level-2 files.
Compliant with FAIR principles	No
Data Management Plan	Unknown
Availability Status	All contracted data are available

Product Format, Flags, & Metadata	
Grade: Good	
Justification	The user documentation provided some information on the quality control. Data quality flags were not well documented in version 1. More information on the quality flag variable (mask) is provided in the new version (V02) of cicPrf but was not available in time to be evaluated by the team.
Product File Format	netCDF4, BUFR
Metadata Conventions	The Level-1 and Level-2 data fields, metadata and data variable organization are inconsistent with the definition used by the GNSS-RO community (eg. CDAAC).

User Documentation		
Grade: Good		
Justification	• The user documentation offers essential information about the GeoOptics instruments, their data processing methods, and data products. However, gaps remain in key details, i.e., data used to constrain the top of the atmospheric profiles are not described or mentioned in the documentation. • Additional information was provided at the end of the evaluation period but not reviewed by the team.	
Document	***Reference***	***QA4ECV Compliant***
Product User Guide	• GeoPRO 1DVAR User Guide v1.0 (Sep 2023) • GeoPRO User Guide v2.0 (Dec 2023) • GeoOptics Data Guide v1.1 (CICERO Reprocessed Data Product Guide - Dec 2023) • GeoOptics QC update to their podtec files (9-25-2023) • Data Guide & Catalog for GNSS RO Products (Submission to NASA)	No
ATBD	Not available.	N/A
Analysis Ready Data?	Yes.	

2.2 Metrology

Calibration & Characterization	
Grade: Good	
Justification	The provided data have some limitations, such as cutoffs in bending angle profiles above 24 km and humidity profiles above 10 km, with no data available above these heights. The BUFR files lack local RO ray azimuthal angle metadata, which may prevent certain 2D forward operators, like the ECMWF model, from assimilating the data without additional adjustments.
References	Vendor documents: • GeoOptics Data Guide v1.1 (CICERO Reprocessed Data Product Guide - Dec 2023) • GeoOptics QC update to their podtec files (9-25-2023) • Data Guide & Catalog for GNSS RO Products

Metrological Traceability Documentation	
Grade: Basic	
Justification	The biases and uncertainties of the GeoOptics bending angle data are comparable to those of established RO missions like COSMIC-2. However, GeoOptics processing introduces non-physical, abrupt changes in these metrics at different levels and times. GeoOptics data could be valuable for assimilation into reanalysis and other research purposes, if they maintain consistent bias and uncertainties throughout the entire observation period.
References	Vendor documents: • GeoOptics Processor for Radio Occultation User Guide • CICERO Reprocessed Data Product Guide CSDA GeoOptics Evaluation PI reports

Uncertainty Characterization	
Grade: Good	
Justification	The cicPOD files provide useful information on orbital position, clock bias, and uncertainty estimation. However, there are several issues with the GeoOptics data, including inconsistent signal-to-noise ratio (SNR) values between the Level-1A occultation files and the Level-1B phase files. The quality mask is defined for each height level, but there is no overall profile quality indicator. The GeoOptics Level-2 bending angle for October 2020 and January 2021 may have a large uncertainty due to their abnormal noise level, the underlying cause of which remains unclear. There is a concern regarding the stability of product uncertainty. The quality control (QC) of the ionospheric data is not adequately described.
References	CSDA GeoOptics Evaluation PI reports

Ancillary Data	
Grade: Good	
Justification	Several ancillary files, including GNSS orbit and clock files, Earth orientation data, DCB (differential code bias) files, Universal Time Code (UTC) tables, GNSS satellite problem history, Jet Propulsion Laboratory (JPL) planet ephemeris, atmospheric tide load, and GNSS satellite antenna parameters, were used in daily POD processing alongside Level-1A RINEX and attitude files. Most of these files are sourced from the University of Bern. Additionally, minor modifications were made to the Bernese GNSS software to accommodate a new LEO satellite due to its slightly different attitude format.
References	Vendor documents: • GeoOptics Processor for Radio Occultation (GeoPRO) User Guide • CICERO Reprocessed Data Product Guide CSDA GeoOptics Evaluation PI reports

2.3 Product Generation

Level-1 Processing Algorithm	
Grade: Basic	
Justification	The Level-1 data can be processed to retrieve the bending angle profile using the common Radio Occultation Processing Package (ROPP) package, but the GeoOptics Level-1 processing algorithms are not adequately documented. The cicPrf data combines both Level-1B (amplitude and excess phase of RO signal) and, when available, Level-2 data (retrieved bending angle and refractivity), but some metadata fields are either missing or of questionable quality. In addition, minor issues were found in the cicPOD (Level-1B) and cicPrf (Level-2) files: the attributes for the 'time' variable indicates start-time as 'Elapsed time since LEO orbit starting time', the actual time seems to be GPS seconds starting from 01/01/1980.
References	• CSDA GeoOptics Evaluation PI reports • GeoOptics Processor for Radio Occultation (GeoPRO) User Guide

Level-2 Processing Algorithm	
Grade: Good	
Justification	The Level-2 processing algorithms are adequately documented. GeoOptics Level-2 data quality consistency and stability is a concern. The varying data quality for different times and satellites may indicate a problem in the processing algorithm. GeoOptics Level-2 data may also have issues in shallow penetration depth in areas of strong convection or moisture, dependence of quality control schemes on specific factors, noisy bending angle retrievals, and increased refractivity errors at higher levels. These problems appear to stem from the GeoOptics data processing algorithm rather than the raw measurements themselves.
References	Vendor documents: • GeoOptics Processor for Radio Occultation (GeoPRO) User Guide • CICERO Reprocessed Data Product Guide CSDA GeoOptics Evaluation PI reports

3. Detailed Assessment of Level-1, Level-2 Data

3.1 Level-1 Signal-to-Noise Ratio (SNR)

Other GNSS-RO (e.g., COSMIC-2, Spire) SNR data were employed to assess GeoOptics measurements.

3.1.1 Assessment Dataset

Grade: Good

Justification:

- Inconsistent signal-to-noise ratio (SNR) values between those in Level-1A occultation files (ogngns) and in the Level-1B excess phase files (cicPrf).
- Quality mask is defined at every height level, with no good/bad overall profile quality indicator.
- Compared to COSMIC-2, GeoOptics has significantly low signal-to-noise ratio (SNR) but its Level-2 profiles retain vertical structure in lower levels which is essential for PBL studies.

3.1.2 Assessment Method

Grade: Good

Methods used in assessments:

- The method involved comparisons of SNR measurements in the free space, and the quality comparison of Level-2 RO retrievals from both CDAAC and GeoOptics across various atmospheric layers because SNR may affect the quality of Level-2 products such as those in the tropopause and planetary boundary layer (PBL). Despite generally lower SNRs, GeoOptics data demonstrated improved penetration to lower atmospheric levels in polar regions, positioning it uniquely for polar PBL studies, especially when compared to Spire and COSMIC-2, which are limited by vertical structure and high-latitude coverage.

- The SNR analysis also included assessment of biases and random error variance relative to reanalysis data. Lower SNRs may affect ionospheric Total Electron Content (TEC) mapping and perturbations and impact the new data for scientific applications.

3.1.3 Assessment Completeness

Grade: Good

All Level-1A, Level-1B and Level-2 data delivered by GeoOptics were evaluated in terms of spatiotemporal sampling, vertical and geographical coverage, sensitivity to PBL properties, as well as statistical error in the upper stratosphere. However, a significant percentage (~40%) of the cicPrf files contained only excess phase (Level-1b) data and no bending angle data (Level-2), perhaps due to quality control in the processing algorithm.

3.2 Level-1 Excess Phase

3.2.1 Assessment Dataset

Grade: Good

The quality of the GeoOptics Level-1B excess phase data were compared to data independently processed with the Radio Occultation Processing Package (ROPP) used by the data assimilation community. The comparisons included the excess phase profiles from the POD and RO antennas.

Justification:

- The GeoOptics cicPOD files provide post-processed low Earth orbit (LEO) orbital positions in Earth-centered inertial (ECI) coordinate frame (J2000), while the Level-1A Standard Product #3 (SP3) format files come from the onboard POD solution. It would be beneficial if GeoOptics post-processed orbital data included SP3 files in International GNSS Service (IGS) format to enable direct comparison in the Earth-centered, Earth-fixed (ECEF) coordinate system. Additionally, the latitude and longitude of the perigee point for the RO profiles are missing, and some of the starting time metadata attributes in the cicPOD and cicPrf files are inaccurate. Furthermore, while the quality mask is defined at each height level, there is no overall quality indicator to distinguish between good and bad profiles.
- The GeoOptics opnGns files contain RO datasets, including GPS time, carrier phase, pseudo-range, carrier phase model, and SNR for L1 and L2 signals. A data reader for these files is available from the University Corporation for Atmospheric Research (UCAR), as noted in the GeoOptics documentation. The files provide high-rate occultation data at a 50 Hz sampling rate from a forward-view RO antenna, meaning only setting occultation data is available. However, the modeled carrier phase values can be large or negative, requiring modifications to the UCAR data reader for properly formatted output.

- The POD processing was evaluated for May 30, 2020, using the Bernese software, with RINEX and attitude files combined into daily datasets. Results showed strong agreement between Bernese and cicPOD, confirming that SP3 files are "on-orbit" products while cicPOD files are post-processed. Since cicPOD positions are in J2000 ECI without a provided transformation matrix, they were converted to ECEF using polynomial interpolation, aligning time series with GPS times and achieving agreement within ±1 m. Clock bias comparisons between Bernese and cicPOD also showed good agreement, though significant drifts, jumps, and resets were observed, with drift decreasing over time for GeoOptics #85 satellite. Overall, the POD input files from GeoOptics are compatible with Bernese, making them suitable for further processing, while cicPOD files provide valuable orbital and clock bias data along with uncertainty estimates.

3.2.2 Assessment Method

Grade: Excellent

Justification:

- The Level-1b data products were evaluated for scientific analysis of mapping ionospheric TEC, and its perturbations, and for its impacts on scientific applications.
- GeoOptics Level-1 RO data were evaluated by comparing with the data processed by the COSMIC Data Analysis and Archive Center (CDAAC) algorithms and the NOAA end-to-end RO data processing system. The GeoOptics Level-1A data is suitable for POD processing using Bernese, with RINEX files provided in IGS RINEX 3.02 format at a 1 Hz sampling rate.
- In addition, the data were evaluated in terms of accuracy, precision, vertical resolution, and sampling statistics for ionospheric applications.

3.2.3 Assessment Completeness

Grade: Excellent

Justification:

Evaluations covered all important GNSS-RO products in Level-1A, Level-1B and Level-2 files, including product information, seasonal and spatial sampling, documentation, retrieval solution, data quality and consistency over time.

3.3 Level-2 Atmospheric Products

3.3.1 Assessment Dataset

Grade: Good

COSMIC-2 and NOAA analysis data were used to assess the GeoOptics atmospheric products.

Justification:

- The retrieved bending angle profiles from GeoOptics RO measurements may be biased or have uncertainties due to satellite RO receiver and positioning antenna characteristics, clock errors, attitude/positioning errors, or variations in the quality control (QC) criteria used in the excess phase to bending angle retrieval.

- There is a much lower success rate of converting to valid bending angle profiles (after quality control) in comparison with COSMIC-2.

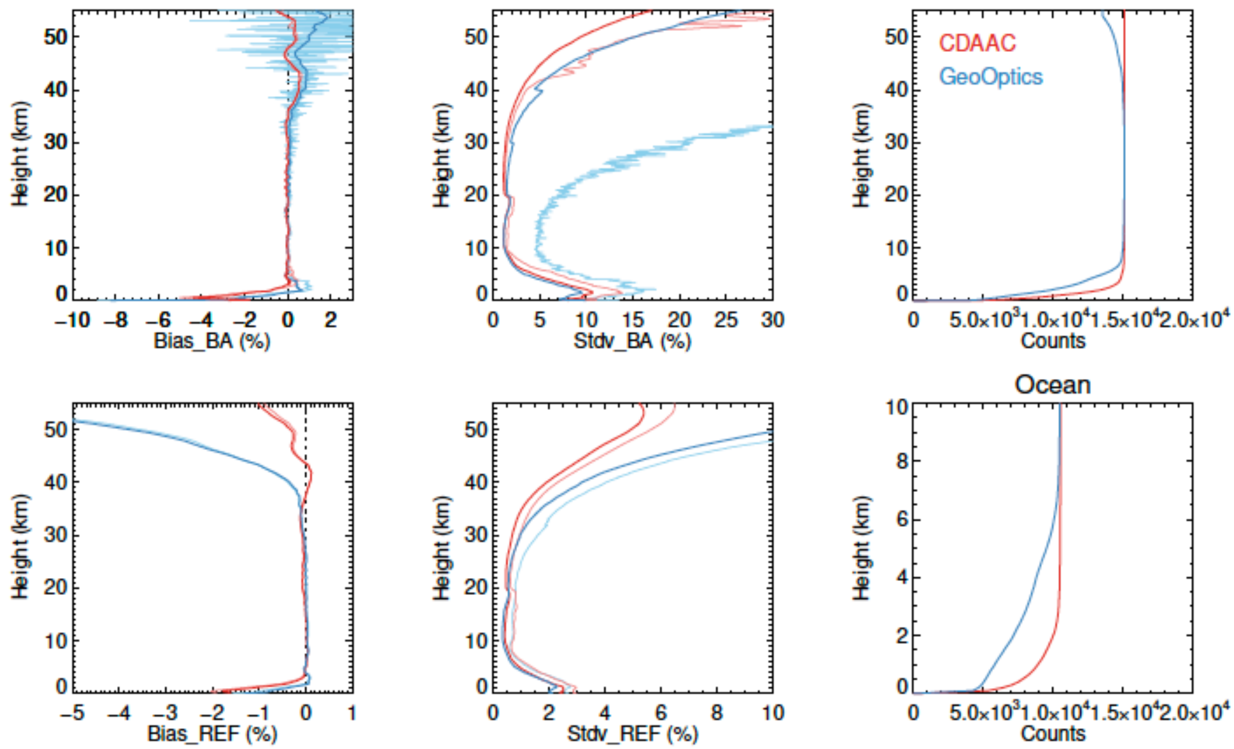

Figure 4. Mean (left) and standard deviation (middle) of BA (upper) and refractivity (lower) differences between ECMWF short-term forecasts and GeoOptics ROs processed by CDAAC (in red) and GeoOptics (in blue), along with the data counts at each level passing all QC checks. Light colors represent statistical results using the conventional method, while dark colors denote results from robust statistics.

- GeoOptics Level-2 1DVAR (temperature and humidity) data are generally consistent with collocated radiosonde and microwave sounder measurements. However, GeoOptics RO data show a substantial day-to-day variation in data volume, and the Level-2 data stability and quality appear to vary with time and between flight modules (FMs). There are anomalies in FM-85 bending angle data in 2021-01 and spikes in FM-85 and FM-87 refractivity uncertainties around 2020-10.

3.3.2 Assessment Method

Grade: Excellent

Justification:

- The quality of GeoOptics bending angle and refractivity data was assessed through comparisons with COSMIC-2 data using two methods: simultaneous RO (SRO) and collocation. The SRO method compares data from two LEO satellites within 15 minutes and a 30 km distance, while the collocation method allows for a time difference of less than 1 hour and a distance of less than 150 km.

- Bias evaluations for GeoOptics satellites #85, #87, and #88 (from 2020 to April 2021) consisted of comparison of their bending angle and refractivity data with the European Centre for Medium-Range Weather Forcasts (ECMWF) Re-Analysis model 5 (ERA5) profiles. This involved forward modeling to derive refractivity and bending angles from atmospheric data. The analysis showed that GeoOptics data were consistent with the ERA5 model, especially for satellites 85 and 87. Data from both GPS and GLONASS (Russian Global Navigation Satellite System) were also in agreement, with only small biases and uncertainties observed.
- Applications for crucial meteorological layers were assessed, including the tropopause and PBL in the lower atmosphere.

3.3.3 Assessment Completeness

Grade: Excellent

Justification:
The quality of GeoOptics bending angle and refractivity data was assessed through inter-comparison with COSMIC-2 mission data using both simultaneous RO (SRO) and collocation methods such as the O-B (background model) for profile bias evaluation and ERA5 for background comparisons. The data from GPS and GLONASS sources were evaluated separately between GeoOptics satellites #85, #87, and #88 with biases and uncertainties as a function of time at various heights.

3.4 Level-2 Ionospheric Products

3.4.1 Assessment Dataset

Grade: Good

GeoOptics satellites #85, #87, and #88 podTEC data were compared to COSMIC-2 podTc2 data.

Justification:

- GeoOptics data files have a format that is not consistent with the conventional format from the user community, which created inconvenience for comparative analyses. For example, COSMIC-2 provides one file per occultation, which is typical for researchers, while GeoOptics provides one file per satellite downlink, resulting in 4 to 8 files per satellite daily. Each GeoOptics file contains about 44 occultations. The cicPOD files offer LEO orbital positions in ECI, which are post-processed, but SP3 files in IGS format would be more suitable for direct comparison in the ECEF coordinate system. Additionally, the time attributes in both cicPOD and cicPrf are misleading, as they are defined using GPS seconds rather than actual elapsed time.

- The GeoOptics data have a low probability of occultation data from the POD antenna for ionospheric profiling, compared to COSMIC-2, due to the lack of the measurements from negative elevation angles.
- Qualitative and quantitative analysis was conducted to assess the accuracy of the provided observations and ancillary data. Some inaccurate or missing information was identified in the GeoOptics occTEC and podTEC data products, documentation, data structure and metadata. For example, the "time" coordinate in the metadata is stated to have units of "seconds" instead of "GPS seconds". Ionospheric measurements with 1 Hz data are advertised to cover between 125 km and 375 km, which represent approximately 5% of the data.

3.4.2 Assessment Method

Grade: Good

Methods for the assessment include comparison of GeoOptics measurements with ionosondes and COSMIC2 for F_2-layer peak density and height.
In addition, sampling statistics of elevation angles between -25 degrees to 90 degrees were compiled to quantify valid ionospheric observations. When the elevation is positive, the LEO satellite 'looks up' to see the GNSS satellite, and when elevation angle is negative, the LEO satellite 'looks down' to see the GNSS satellite. To be considered an occultation, the elevation angle must be negative at some point in the file.

Justification:

- Both COSMIC-2 and GeoOptics data agree well with ionosondes, with a slightly better results with COSMIC-2.
- The Level-2 occTEC data product as provided is not useful for any meaningful scientific applications due to limited vertical coverage.

3.4.3 Assessment Completeness

Grade: Excellent

Justification:

- GeoOptics podTEC data are of high quality and accuracy. GeoOptics data provides additional data at midlatitudes and helps address the lack of COSMIC-2 data at high latitudes. Its absolute TEC appears to be accurate and suitable for science, and its relative TEC proved a decent match for ionosonde data.

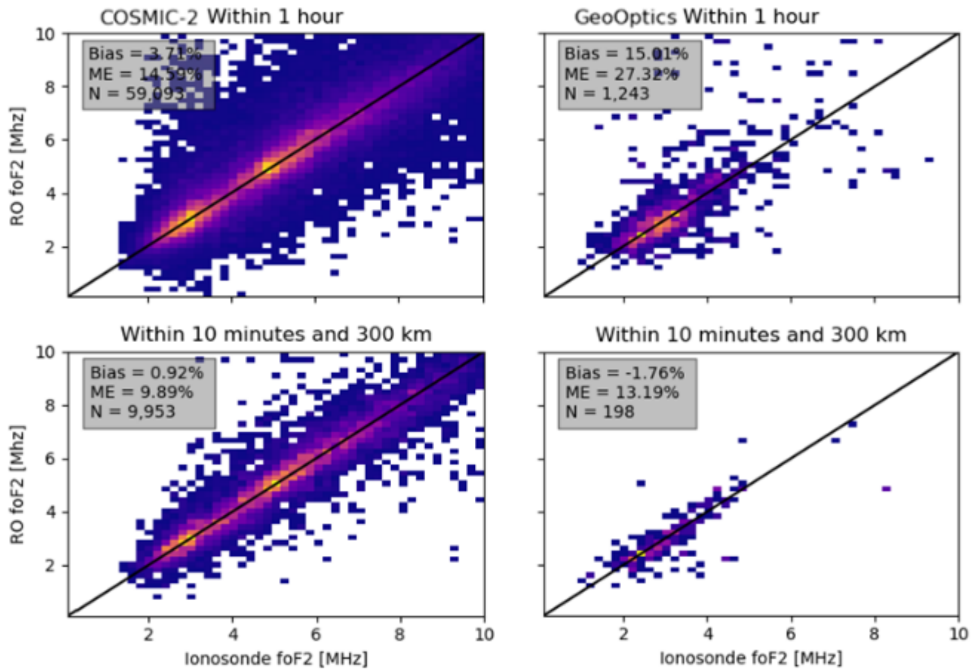

Figure 5. Comparison of F_2 (F_2-layer peak frequency) with ionosondes for COSMIC-2 and GeoOptics

4. References

GeoOptics. (2022). Data Guide & Catalog for GNSS RO Products, Attachment C, BPA submission to NASA.

GeoOptics. (2023a). The GeoOptics Processor for Radio Occultation (GeoPRO) User Guide, Version 2.0, Dec 2023.

GeoOptics. (2023b). CICERO Reprocessed Data Product Guide, Version 1.1, Dec 2023.

GeoOptics. (2023c). GeoPRO 1DVAR User Guide, Version 1.0, Sept. 2023.

GeoOptics. (2023d). GeoOptics QC update to their podtec files, communication from Alex Saltman, 10-25-2023.