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COSMIC-2 Mission Summary at Three Years in Orbit

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Abstract: We summarize the status of the FORMOSAT-7/COSMIC-2 (COSMIC-2) mission which has completed its first three years in orbit. COSMIC-2 is a joint U.S./Taiwan program consisting of six satellites in low-inclination orbits with the following payloads: Global Navigation Satellite System radio occultation, in-situ ion velocity meter, and tri-band radio frequency beacon. The constellation is in its final orbit configuration and reached mission full operating capability in September 2021. An extensive calibration/validation campaign has to date enabled the release of all baseline neutral atmosphere products and nearly all baseline ionosphere products. The mission is providing usually more than 5000 neutral atmosphere RO profiles per day with a precision better than 2 μrad from 30–60 km altitude. Each day, nearly 12,000 combined total electron content occultations and arcs are generated with absolute accuracy of better than 3 TECU. IVM density precision is at or below the 1% requirement. Neutral atmosphere and ionosphere latency, measured from time of observation to product creation time, is below 30 min median. Data products are delivered in near real-time to operational weather and space weather centers and made available openly to the research community. New ionosphere products specifying the presence and absence of scintillation are under development and planned for future release.

Keywords: FORMOSAT-7; COSMIC-2; satellite mission; radio occultation; neutral atmosphere; ionosphere

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1. Introduction

The six-satellite FORMOSAT-7/COSMIC-2 (COSMIC-2) mission, a Taiwan-U.S. partnership, launched in June 2019 and has now completed nearly 3 years in orbit [1]. The constellation is deployed into six evenly spaced circular orbital planes with 24 deg inclination at an altitude of approximately 550 km. Each satellite carries as its primary payload a Tri-GNSS (Global Navigation Satellite System) Radio-occultation (RO) System (TGRS) instrument developed by NASA's Jet Propulsion Laboratory (JPL), which observes atmospheric bending, refractivity in the troposphere and stratosphere and absolute total electron content (TEC), and electron density and scintillation in the ionosphere [2]. Secondary payloads are the Ion Velocity Meter (IVM) developed by the University of Texas at Dallas and tri-band Radio Frequency Beacon (RFB) developed by SRI International [3,4]. The IVM measures in-situ ion plasma density, composition, temperature, and velocity. The RFB is a transmitter enabling measurements of TEC and scintillation by terrestrial receivers. The COSMIC-2 instruments are currently producing upwards of 5000 daily high signal-to-noise ratio (SNR) and high-vertical-resolution profiles of neutral atmosphere bending angle, refractivity, and temperature in the tropics and subtropics; ionosphere products including typically more than 10,000 slant TEC tracks, ~4000 electron density profiles, and scintillation indices; in situ plasma density, composition, temperature, and drift. Neutral atmosphere bending angle and refractivity are assimilated by operational and research numerical weather prediction models [5–7]. Ionospheric data products are utilized by operations and research centers for space weather specification and prediction [8,9].

Multiple detailed scientific studies on the accuracy and utility of COSMIC-2 data products for neutral atmosphere and ionosphere applications have been published since launch, e.g., [1,10–16].

COSMIC-2 follows upon the successful FORMOSAT-3/COSMIC (COSMIC) mission that operated from 2006–2020. Some key differences between COSMIC-2 and COSMIC are: COSMIC had global coverage, whereas COSMIC-2′s low-inclination orbit configuration provides dense sampling between approximately ±40 deg latitude and no coverage outside this range; the COSMIC-2 spacecraft are larger and heavier, providing better attitude stability and room for larger payload packages; COSMIC-2′s precise orbit determination (POD) antennas have choke-rings to reduce local multipath effects; the COSMIC-2 RO antennas are phased arrays that steer gain in the direction of neutral atmosphere occultations in order to increase the SNR and enable tracking deeper into the troposphere; COSMIC tracked the Global Positioning System (GPS) only, while the COSMIC-2 TGRS tracks both GPS and Global'naya Navigatsionnaya Sputnikovaya Sistema (GLONASS) navigation signals; the TGRS collects high-rate POD antenna measurement if scintillation is detected along a link; COSMIC-2 data products are available with significantly lower latency due to an extensive downlink station network. Also, the IVM and RFB payloads are new to COSMIC-2.

At this point the COSMIC-2 mission has completed several important programmatic and scientific milestones and is making significant contributions to neutral atmosphere and space weather operations and science applications. To summarize the mission's achievements and plans, this paper surveys the COSMIC-2 mission from several vantage points. We begin with current mission status, operations, and major milestones since launch. Next, we cover the verification of select mission requirements, available data and products generated in near real-time and post-processing modes. We also describe plans for future data products.

2. Mission Status and Milestones

2.1. Satellite Constellation

All flight models (FMs) were initially launched into a single, 720 km high orbit plane and lowered one at a time to their final operational altitude of ~550 km. This allowed the individual orbit planes to precess relative to one another, such that the final orbits are evenly spaced in right ascension of the ascending node (RAAN). The final orbit configuration was achieved on 20 February 2021. Key orbital parameters, and the timeline for lowering each FM, are summarized in Table 1. During orbit lowering, all payloads for the respective FM were turned off. While the maximum latitudinal extent of the ground tracks is ±24 deg, the RO profiles provide both full geographic and local time sampling up to approximately ±40 deg latitude.

Table 1. Current satellite orbit information and adjustment dates (payloads off).

Flight Model	Current Apogee Orbit Altitude, Inclination, RAAN	Orbit Adjustment Dates
1	546 km, 24 deg, 245 deg	22-07-2019 to 15-08-2019
2	547 km, 24 deg, 360 deg	05-11-2019 to 22-11-2019 and 21-02-2020 to 23-03-2020
3	545 km, 24 deg, 70 deg	08-06-2020 to 16-07-2020
4	542 km, 24 deg, 307 deg	15-11-2019 to 21-01-2020 and 15-02-2021 to 20-02-2021
5	543 km, 24 deg, 125 deg	23-09-2020 to 19-10-2020
6	539 km, 24 deg, 184 deg	10-01-2021 to 03-02-2021

2.2. Payloads

The primary TGRS payload tracks dual frequency GNSS pseudorange and carrier phase from two pairs of POD and RO antennas facing in the forward and anti-velocity directions. Dual frequency pseudorange, carrier phase, and signal to noise ratio measurements from the POD antennas are used for satellite orbit and clock determination, and to derive TEC, electron density profiles, and scintillation amplitude and phase indices. The RO antennas track dual-frequency open-loop carrier phase, used to derive neutral atmosphere bending angle profiles and associated products. Over the course of the mission the TGRS flight software has been updated to address issues discovered and enhance capabilities. There have been seven updates so far. Their main features and timelines are given in Table 2.

Table 2. TGRS flight software updates.

Software Version	Key Features	Date
v4.3.2	Corrected reboot issue.	September 2019
v4.3.3	Reduced troposphere & ionosphere data loss; corrected GLONASS pseudorange noise problem; connected phase for GLONASS high-rate (HR) ionosphere data.	November 2019
v4.3.4	Improved tracking channel allocation; provide 1 sec SNRs (instead of 10 sec); connected phase for GPS HR data; address connected phase problem for GLONASS high rate ionosphere data; improved HR scintillation trigger algorithm.	February 2020
v4.3.5	Improved GPS & GLONASS observation scheduling; corrected GPS HR L2 & HR scintillation incomplete profile problems; fixed issue with high-rate scintillation data volume limiting algorithm.	August 2020
v4.3.6	Improvements to GLONASS scheduling & channel management; improved autonomous detection of hangup events requiring reboot.	February 2021
v4.4.0	Improved ionosphere tracking through sporadic-E layers; improved GLONASS observation scheduling; improved acquisition of rising L2P signals; correct issue with corrupted GLONASS HR data.	September 2021
v4.4.1	Reduced time to resume tracking following restarts; improvements to GLONASS ionosphere scheduling and tracking through larger azimuth ranges.	December 2021
v4.4.2	Further improvements to tracking through sporadic-E layers; correct occasional issue with occultation height of straight-line computation; improved trigger to collect more HR ionosphere data.	July 2022

Two secondary payloads are the Ion Velocity Meter (IVM) and radio frequency beacon (RFB). The IVM measures in-situ plasma density, composition, temperature, and velocity [3,16]. The tri-band RFB emits signals in the UHF, L, and S bands for reception and processing on the ground to monitor scintillation [4]. Since RFB data must be collected by individual ground stations they are not processed centrally and have thus not been part of the program's formal data releases.

2.3. Ground Segment

A network of 10 downlink ground stations located in Australia, Brazil, French Polynesia, Ghana, Guam, Hawaii, Honduras, Kuwait, Mauritius, and Taiwan receives downlink telemetry and routes the data to the National Space Organization (NSPO) and University Corporation for Atmospheric Research (UCAR) data processing centers. The sites in Taiwan, Australia, and Mauritius are capable of uplink/commanding. A map is given in Figure 1. The network is designed to enable frequent downlinking of COSMIC-2 data in order to meet the mission data product median latency requirements of 45 min and 30 min for neutral atmosphere and ionosphere products, respectively.

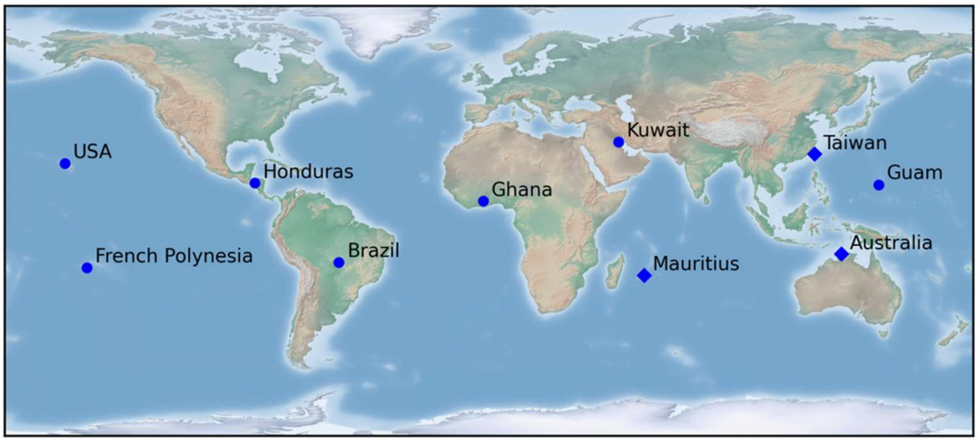

Figure 1. COSMIC-2 ground station locations. Circle markers denote downlink stations and diamond markers indicate downlink/uplink capable stations.

2.4. Data Processing Centers

There are two data processing centers (DPCs) operated by UCAR's COSMIC Program and the Taiwan Central Weather Bureau (CWB). Both receive the level 0 downlink data and perform processing to level 1 and 2 products in near real-time (NRT) with the COSMIC Data Analysis and Archive Center (CDAAC) software framework [17]. The CWB additionally runs the TROPS system [18]. The DPCs are configured and maintained to provide automated processing with high availability.

The processing steps are as follows:

- Data intake and level 0 (mission/instrument specific) to level 1 (generic) data format conversion;
- Precise orbit determination (POD) using dual frequency pseudorange and phase with fixed precise orbits and clocks for the GPS constellation, using the aft POD antenna by default, typically achieving a precision of 10–15 cm 3D RMS [19,20];
- Neutral atmosphere RO processing including computation of excess phase, bending angle and refractivity retrieval, and 1D-var retrieval using the European Centre for Medium-Range Weather Forecasts (ECMWF) operational short-term forecast as background [1,21];
- Ionosphere processing including (1) ionospheric excess phase and electron density profiles [14], (2) absolute TEC for GPS and GLONASS [15,22], (3) computation of scintillation amplitude, phase indices and geolocation, (4) IVM plasma composition, temperature, density, and velocity [16];
- Quality control, packaging in external data formats as required, and delivery of products to users [17].

In addition to NRT processing, the DPCs run post-processing on a monthly basis. The main differences versus NRT processing are:

- Collection of all available data (including downlinks delivered too late for NRT) into 24 h batches;
- Utilization of International GNSS Service Final GNSS orbits and clocks (the highest precision product);
- Daily POD using a 24 h arc;
- Utilization of the ERA5 short term-forecast as the 1D-var background.

Finally, from time to time, all data are reprocessed using consistent algorithms and configuration in a manner similar to post-processing to benefit climate applications of the data. For COSMIC-2, this is being done the first time in summer 2022 for data going back to 1 August 2019. The data are expected to be released in the second half of 2022.

2.5. Program Milestones

Since launch and instrument activation the program team worked extensively to check-out spacecraft and payload health, verify performance, and make initial configuration and software adjustments. Following this, on-orbit neutral atmosphere and ionosphere calibration/validation activities commenced and progressed, resulting in operational/validated product releases as individual milestones were reached. To date, there have been two and five neutral atmosphere and ionosphere data releases, respectively, and several important program milestones have been reached, as summarized in Table 3.

Table 3. Major post-launch program milestones.

Milestone	Date	Comments
First payload activation	16-07-2019	Checkout begins
Satellite IOC	22-10-2019	Formal program review
Neutral atmosphere data release 1	10-12-2019	Provisional TGRS products
Neutral atmosphere IOC	24-02-2020	Formal program review
Neutral atmosphere data release 2	06-03-2020	Validated TGRS products
Ionosphere data release 1	30-03-2020	Provisional TGRS relative TEC, onboard S4, electron density profiles
Ionosphere data release 2	18-09-2020	TGRS GPS absolute TEC
Ionosphere IOC	19-11-2020	Formal program review
Ionosphere data release 3	29-01-2021	TGRS GLONASS absolute TEC
Ionosphere data release 4	29-03-2021	IVM ion density
Neutral atmosphere FOC	31-03-2021	Formal program review
Mission FOC	15-09-2021	Formal program review
Ionosphere data release 5	16-03-2022	High rate observation scintillation indices, early orbit IVM ion temperature, composition, and drift

The team supporting calibration and validation of TGRS neutral atmosphere products consists of experts from The Aerospace Corporation (Aerospace), CWB, JPL, Joint Center for Satellite Data Assimilation, National Central University, NOAA, NSPO, and UCAR (neutral atmosphere cal/val lead). Metrics evaluated include RO profile counts and distribution, bending angle noise metrics, bending angle/refractivity/temperature comparison to global numerical weather prediction (NWP) forecasts/analyses, evaluation of 1D-var retrieval products, inter-comparisons with other RO missions (e.g., KOMPSAT-5, MetOp, PAZ) and radiosondes, NWP assimilation system observation-background statistics, and NWP impact studies [1,5,6,11]. Provisional neutral atmosphere products were released in December 2019, following initial validation of the retrieved products. The neutral atmosphere Initial Operational Capability (IOC) was achieved in February 2020, based on: stable and routine processing in place at both DPCs; early orbit inter-satellite product comparisons showed precision metrics meeting requirements; products compared against global NWP solutions, other RO missions, and radiosondes, and shown to meet requirements; verification that GPS and GLONASS profiles yielded consistent results, or differences understood; issues encountered were documented, and open issues tracked with plans to close them defined. Following a successful review, validated products were released in March 2020. Neutral atmosphere FOC was achieved in March 2021, following verification of product quality, level 1 science requirements, and operations performance after all satellites reached the final orbit configuration.

The team supporting calibration and validation of ionosphere products consists of experts from Aerospace (ionosphere cal/val lead), CWB, JPL, National Cheng Kung University, NCU, NOAA, NSPO, UCAR, University of Texas at Dallas. Electron density profiles and relative TEC were initially verified and released. GPS and GLONASS absolute TEC were validated and released in 2020 and 2021, respectively [23,24]. IVM density data were released in March 2021 [25]. Most recently, in March 2022, IVM temperature and composition validated by comparing to Jicamarca Radio Observatory measurements, and early mission FM1 drifts were released. This release also includes TGRS high-rate scintillation data (downlinked when the onboard computed S4 index exceeds a configurable threshold and there is sufficient downlink capacity), ground computed scintillation amplitude and phase indices for the high-rate observations, and ancillary radio frequency interference information. The scintillation data were verified to successfully geolocate ionospheric irregularity regions using back-propagation analysis, and via comparisons to GOLD ultraviolet imagery [26].

3. Requirements, Products, and Performance

3.1. Key Requirements

The program team conducted extensive pre- and post-launch requirement verification from levels 1–4. In Table 4 we summarize a few of the most important level 1 science threshold requirements and the system's performance to them.

Table 4. Selected level 1 science threshold requirement verification summary.

Description	Requirement	Verification Status
Neutral atmosphere profiles per day passing QC	>4000	Met, typically >5000, ref. Section 3
Neutral atmosphere profile median product latency per day	<45 min	Met, typically ~28 min, ref. Section 3
Bending angle uncertainty, 30–60 km	2 µrad	Met, 1.6 µrad [27].
Refractivity uncertainty, 10–20 km	0.1 N units	Met, 0.076 N units [27].
TEC occultations per day	>6000	Met 33% of days January–May 2022, and 42% of days in May 2022. Average January–May 2022 is 5797 and May 2022 is 5870. Waiver issued. Waiver issued for 91.5% compliance.
Combined TEC arcs and occultations per day	>12,000	Met 31% of days January–May 2022, and 65% of days in May 2022. Average January–May 2022 is 11,626 and May 2022 is 11,948. Waiver issued for 91.5% compliance.
Absolute TEC uncertainty	3 TECU	Met, estimated 2.5 TECU for GPS and 2.6 TECU for GLONASS [15,22]
TEC product median latency per day	<30 min	Met, typically ~28 min, ref. Section 3
IVM in-situ plasma density precision	1%	Met, ref. [25]

The selected TGRS neutral atmosphere science requirements relate to RO profile counts per day after quality control (QC) and retrieved bending angle and refractivity precision. Retrieved profile precision metrics are verified using early orbit data from 16 July–4 September 2019, when all satellites were still in the same orbit plane (REF). These data yield 270 inter-satellite retrieved profile pairs with separations ≤20 km. L2P signal rising occultation are excluded due to a tracking issue in early TGRS flight software (REF memo). This analysis verified bending angle, refractivity, dry temperature precision at various mean sea level (MLS) altitude levels from the surface to 60 km [27]. The 2 µrad 30–60 km precision requirement is especially important as it measures bending angle precision with little contribution from the neutral atmosphere and therefore represents other system error sources including POD, residual ionosphere, and noise. Product latency is well below the 45 min median requirement (Section 3).

Important TGRS ionosphere requirements are the TEC occultation and combined occultation and arc counts per day and absolute TEC uncertainty. GPS absolute total electron content is validated via comparisons to Swarm-B utilizing GPS data in certain regions with minimal ionospheric activity, and GLONASS absolute TEC is verified by comparing

COSMIC-2 GPS and GLONASS TEC observations with closely matching geometries [15,22]. Both TEC products were shown to exceed the 3 TECU precision requirement following extensive calibration. TEC product latency is similar to the neutral atmosphere and has been below 30 min median for nearly all days in 2022 (see Section 3). IVM density data were validated by comparing with TGRS GNSS electron density and deemed to have a precision of 1% or better [25].

3.2. Current Products

The currently available COSMIC-2 products and requirements are summarized in Table 5. The COSMIC-2 data user communities receiving the products may be divided into operational and research categories. Operational data products are delivered to NOAA's Environmental Modeling Center (EMC) and Space Weather Prediction Center (SWPC), US Air Force 557th Weather Wing, US Navy Fleet Numerical Meteorology and Oceanography Center, Taiwan's CWB, ECMWF, and other operational centers worldwide via the WMO Global Telecommunication System [28]. Operational assimilation of COSMIC-2 neutral atmosphere products began December 2019 at FNMOC, March 2020 at ECMWF, and May 2020 at EMC [5,6]. Per the program's data policy, daily near real-time data and products are published about 2 h after the close of each day.

Table 5. Available data products. Unless otherwise noted, file formats are NetCDF and documented at CDAAC and CWB [29,30].

Type	File Format	Comments
Level 0 data	trgLv0	Decoder software available on CDAAC data site
Satellite attitude	leoAtt	
RO antenna observations	opnGns	
POD antenna observations	podCrx (RINEX)	Ref. [31]
POD estimates	leoOrb (SP3)	Ref. [32]
High rate RO observations	opnGns (binary)	
Excess phase	conPhs	Nav bits removed
Neutral atm. retrieval	atmPrf	
Neutral atm. model profiles	avnPrf, echPrf	Derived from Global Forecast System and ECMWF global NWP models
1D var retrieval	wetPf2	
Neutral atm. BUFR	BUFR (binary)	Ref. [33]
Electron density profiles	ionPrf	
Absolute TEC	podTc2	
Scintillation amplitude and RFIindices	scn1c2	Onboard computed amplitude index
High rate POD antenna observations for scintillation monitoring	scnPhs	
Scintillation amplitude, phase and RFI indices	scnLv2	Ground computed from high rate observations
IVM in-situ plasma density, composition, temp	ivmLv2	

The number of neutral atmosphere profiles per day passing quality control (QC) in 2022 is shown in Figure 2. It is clear the mission is reliably exceeding the 4000/day requirement (should be met 91.5% of the time). Occasionally significant drops occurred for operational reasons (e.g., ground station outages). There is also a trend towards lower counts during March–April, due to increased ground processing QC check failures. The cause of a portion (approximately 40%) of this drop has been determined and will be addressed in TGRS flight software v4.4.2. The causes of other QC failure increases are under investigation. Since May 2022, the post-QC counts have improved.

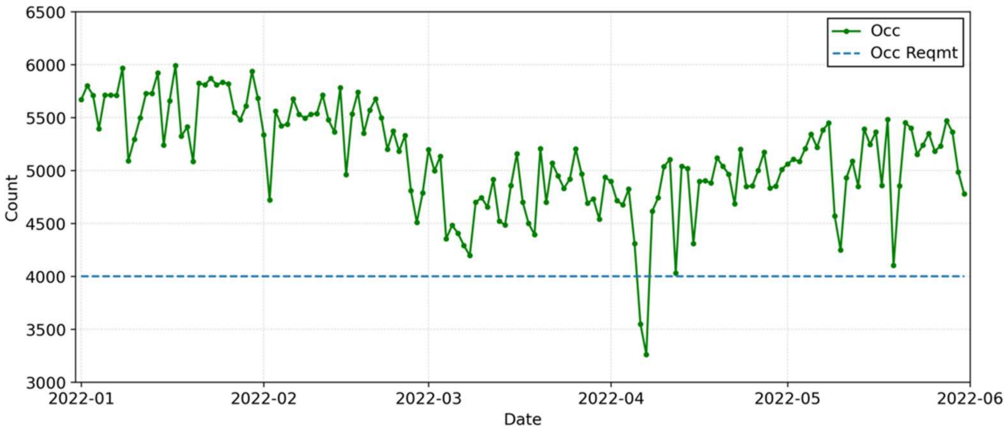

Figure 2. TGRS neutral atmosphere occultations per day passing QC in 2022.

A key feature of the TGRS is a pair of high-gain phased array antennas for RO tracking. This enables higher SNR RO profiles than any other mission to date. Figure 3 shows the daily max, mean, and median SNR in the range of 60–80 km height of straight line (HSL). The average of the daily mean and max SNR is 1277 V/V and 2437 V/V, respectively. For comparison, the mean SNR achieved by COSMIC-1 is approximately 700 V/V [34]. Higher SNR mainly enables the receiver to track signals lower into the troposphere. In fact, COSMIC-2 is configured to track setting profiles to −350 km HSL which enables the reliable detection of tropospheric ducts. In future, detected ducts may be flagged in order to provide more information to data users [1,34].

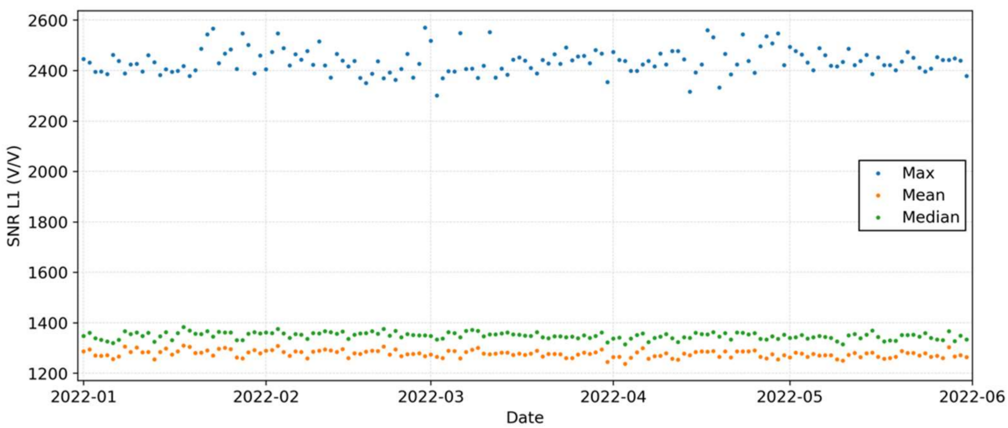

Figure 3. Max, mean, and median daily high-altitude SNR for neutral atmosphere profiles in 2022. For each profile, SNR is averaged between 60–80 km.

TGRS ionosphere product quantity is measured as the number of daily TEC arcs and occultations. A TEC arc and occultation are defined as the portion of a track above and below the spacecraft local level, respectively. An occultation must span from 90 km straight-line altitude to spacecraft altitude in order to be counted. A key requirement related to TEC is that the daily sum of the arcs and occultations should be at least 12,000. Figure 4 shows TEC arcs, occultations, and their sum in 2022. The arc plus occultation requirement has not been consistently met since launch. This has driven significant TGRS and ground processing software improvements and detailed investigation of potential future improvements.

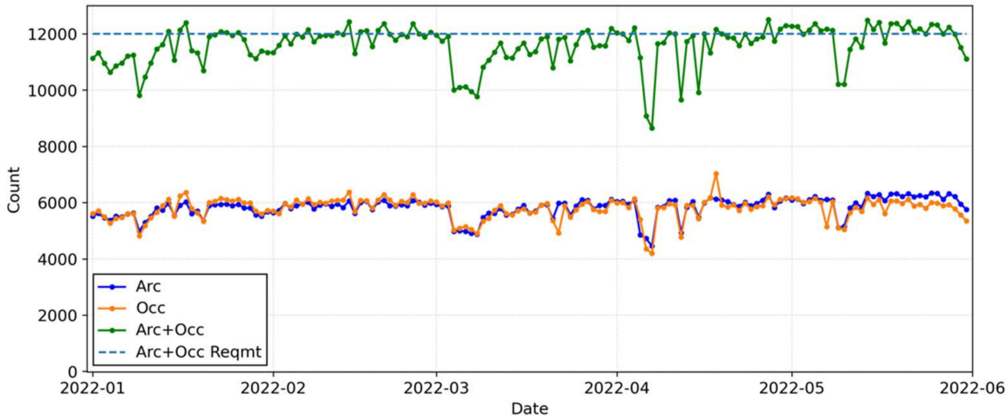

Figure 4. TGRS TEC arc, occ, and arc plus occ scores in 2022.

As mentioned previously, the mission's data product latency requirements drive the implementation of a 10-downlink-station network. Since the addition of the 10th station at Tahiti on 3 January 2022, the latency of both the neutral atmosphere and TEC products exceed requirements on nearly all days, as shown in Figure 5. The time series show the daily median of all computed latency values. The latency values are computed from every 10th 1 s observation epoch in a neutral atmosphere profile or TEC track to the product creation time. This measure includes on-orbit storage time, downlink and transfer to the DPC, and processing time.

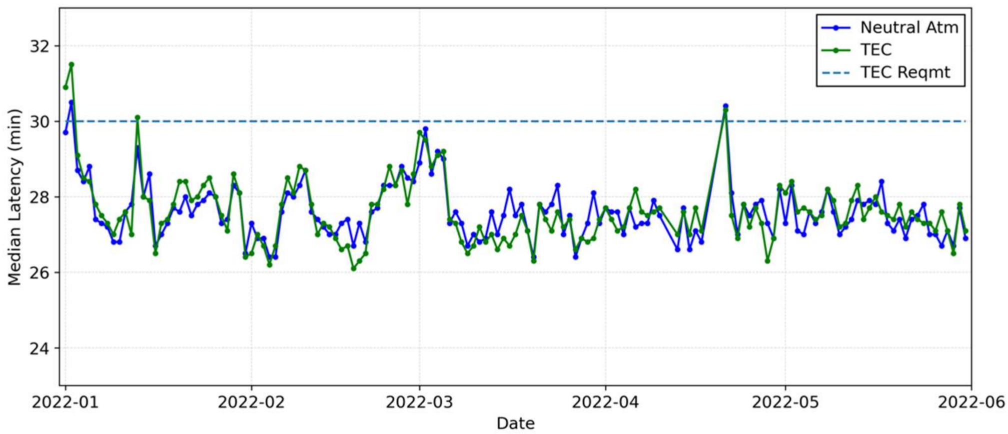

Figure 5. Data product latency in 2022. The 45 min neutral atmosphere requirement line is not shown. Unexplained outlier data on 12 April 2022 are omitted.

COSMIC-2 data and products may be downloaded from CDAAC and CWB [29,30]. Figure 6 below shows the monthly volume and number of files downloaded from the CDAAC public interface in 2022. Data and products are published as one daily compressed tar file per file type. On average, 9.7 TB and 23187 files were downloaded each month.

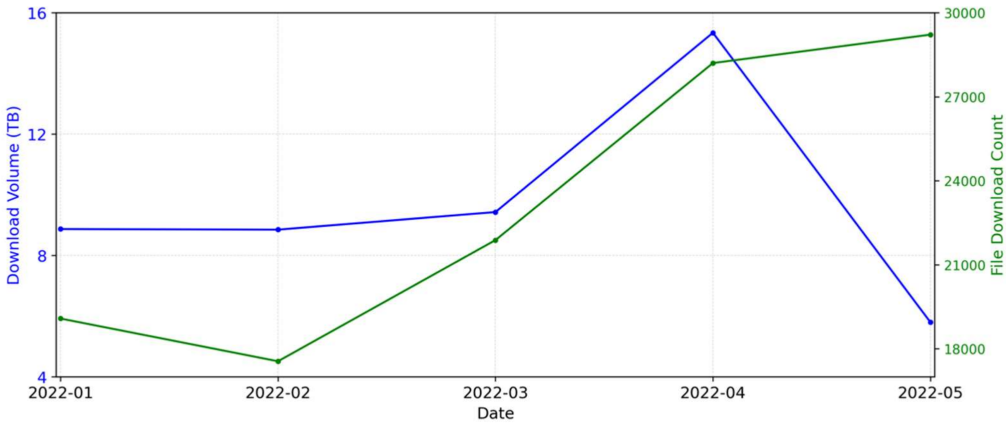

Figure 6. CDAAC COSMIC-2 data download volume and files in 2022.

3.3. Benefits to NWP and Space Weather Operations and Research

Over the last three decades GNSS RO has become a critical component of the global observing system for the study of weather, space weather, and climate applications due to its global coverage, vertical resolution, accuracy, low latency, and relatively low cost. COSMIC-2, now in its final operational deployment, is providing unprecedented geographic and local time sampling of the Earth's atmosphere and ionosphere with the highest signal-to-noise ratio data ever recorded in orbit. The unprecedented sampling provided by COSMIC-2 has unearthed new details on the broad spectrum of large- and small-scale waves near the tropical tropopause region [35]. The high SNR data allow COSMIC-2 soundings to penetrate through the troposphere closer to Earth's surface than other previously flown missions and to detect critically sharp layers on top of the atmospheric boundary layer that induce radio wave ducting called super-refraction [1]. For ionospheric sensing, the RO receiver and four antennas were uniquely designed to provide a wealth of TEC and scintillation observations for every tracked GNSS satellite, especially at low elevation angles that profile the F-layer. This extremely high-quality, low latency, and well-curated dataset made openly available to the science community is currently having significant impact on weather and space weather operations and will continue to benefit research for years to come.

COSMIC-2 has been providing high-quality and low latency bending angle profiles per day to the community for NWP applications since early in the mission in late 2019. The high SNR and high-density sampling coverage up to 40 deg latitude have led to significant improvements in forecasting skill at operational centers. The US Navy and ECMWF centers found improvements in the shortrange forecast departures for temperature, humidity, and zonal/meridional components of the wind, for in situ observations, e.g., radiosonde, and remotely-sensed observations, e.g., ATMS satellite radiances [5]. They also found improvements to the 24 h forecasts as assessed by computing the adjoint-based forecast sensitivity to observation impact metric, and to medium range forecasts by verifying against operational analyses. The positive impact of COSMIC-2 data on tropospheric humidity is a significant new result and represents a large step forward for NWP skill improvement.

Large- and small-scale variations of ionospheric electron density are important to monitor and predict, because they affect radio wave propagation and can impair satellite communication, navigation and electric power grid operations. The COSMIC-2 GNSS RO instrument has for the first time counted the total number of electrons between the receiver and GNSS transmitter, i.e., absolute TEC, to a demonstrated accuracy of $< 3 \times 10^{16}$ electrons/m^2 [15]. These high quality and low latency COSMIC-2 TEC data are now being transferred in near real-time to NOAA SWPC and US Air Force 557th Weather Wing systems where they are being operationally assimilated to produce space weather forecasts. The TEC data as a function of altitude are also used to compute profiles of electron density (electrons/cm^3) as a function of altitude, which have been validated with ground truth ionosonde stations around the globe that show agreement to an impressive ~6–7% for quiet ionospheric conditions [14], and have been assimilated with positive impact into space weather prediction research models [9]. The COSMIC-2 GNSS RO scintillation observations are also being used to geolocate ionospheric irregularities with small uncertainty for use in operations and space weather research [36].

3.4. Future Products

All but one of the mission's baseline set of data products are already in production and published. The final remaining product to be released is IVM in-situ drift. This is undergoing analysis to determine the cause of measurement biases for some instruments and timeframes. Product release is pending resolution of this issue.

The program is also developing and validating the following additional TGRS ionosphere products:

- UHF scintillation "all clear." Utilizes 1 Hz POD signal to noise ratio observations to identify regions where scintillation if unlikely to be present. This product will be generated at rapid cadence (<30 min) to support space weather monitoring.
- Scintillation geolocation. This product applies a back propagation technique to high-rate phase observations collected from the POD antennas when scintillation is detected to estimate where along the ray path the scintillation occurred [36,37].
- Ionosphere "bubble map." Aggregates scintillation geolocations over time to identify regions and times with the presence of ionospheric irregularities.

For the neutral atmosphere, improved algorithms for the detection of super-refraction for COSMIC-2 data are under development and expected to provide additional information to data users.

These new products are expected to be released in late 2022 and 2023. For up-to-date product status, please refer to [29].

4. Conclusions

COSMIC-2′s first three years in orbit have been very successful. Following payload activation and checkout, neutral atmosphere and ionosphere calibration/validation activities began and led to incremental product releases as validation/verification milestones completed. At this time all but one of the baseline products are released and made available to operational centers and the research community. The mission is making clear positive impacts to operational weather and space weather specification and prediction and is contributing high quality data to science applications in the areas of weather, space weather, and climate. In the future, new TGRS ionosphere products specifying the presence or absence of scintillation events will provide additional important information to space weather centers. We also expect that incremental flight software and ground processing updates will further enhance the quantity and quality of both neutral atmosphere and ionosphere data products.

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