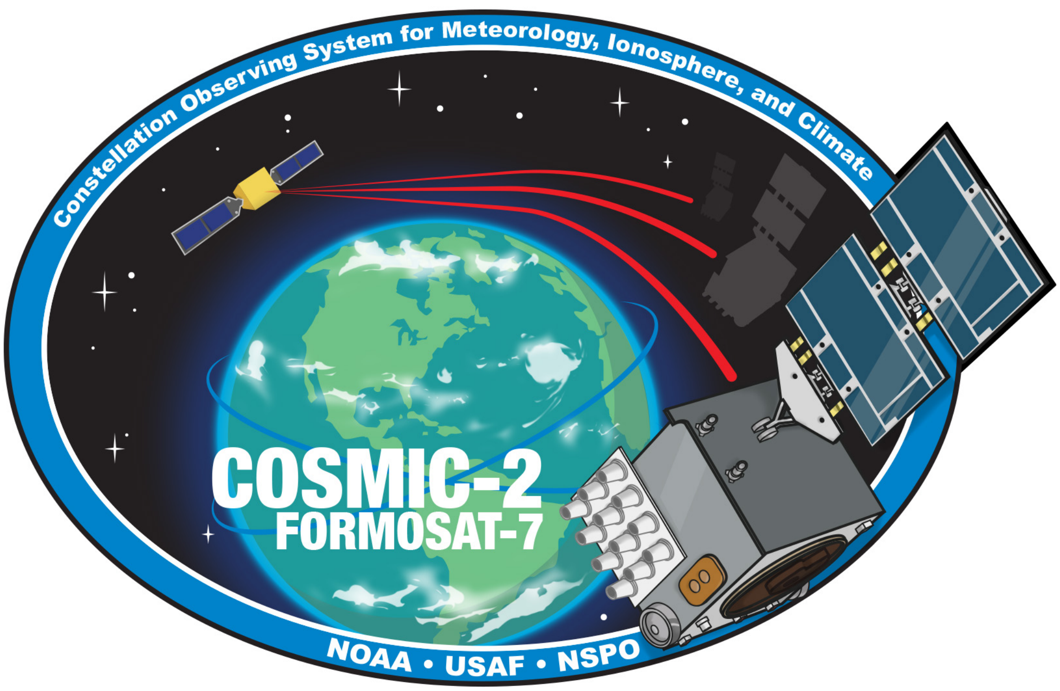
FORMOSAT-7/COSMIC-2
TGRS Space Weather Provisional Data Release 1

March 30, 2020



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1 Background

The United States Air Force (USAF) Space Test Program successfully launched six FORMOSAT-7/COSMIC-2 (F7C2) satellites into a 24 deg inclination low Earth orbit on June 25, 2019. The primary F7C2 mission objective is to continuously and uniformly collect atmospheric and ionospheric data as the inputs to daily near-real-time weather forecasts, climate studies, and space weather monitoring and forecasting. Following spacecraft system activation and checkout, instruments were first activated on July 16, 2019. Each F7C2 satellite has three instruments: the primary Tri-GNSS Radio-occultation System (TGRS) payload, Ion Velocity Meter, and Radio Frequency Beacon. This data release encompasses the TGRS space weather products (relative total electron content (TEC), scintillation amplitude index (S4), and electron density profiles). Summaries of space weather early orbit and cal/val activities are described in [1] and [2]. Other Ionospheric data, including absolute TEC, will be released at a later date.

TGRS space weather products from October 1, 2019 and forward are included in this release. This start date is chosen because all TGRS units operated using consistent flight software and configuration, and because radio occultation (RO) counts are relatively consistent. As such the dataset is useful for evaluation in space weather monitoring and forecasting systems to assess quality and impacts of the F7C2 data. All data are processed as if in near real-time. The following data types are released:

- Level 1b
  Relative TEC and S4 (podTc2 format)

- Level 2
  Electron density profiles (ionPrf format)

See Section 6 for the data download locations and file format descriptions.

2 Provisional Maturity Definition

1. Product performance has been demonstrated through analysis of a large, but still limited (i.e. not necessarily globally or seasonally representative) number of independent measurements obtained from selected locations, time periods, or field campaign efforts.

2. Product analyses are sufficient for qualitative, and limited quantitative, determination of product fitness-for-purpose.

3. Documentation of product performance, testing involving product fixes, identified product performance anomalies, including recommended remediation strategies, exists.

4. Product is recommended for potential operational use (user decision) and in scientific publications after consulting product status documents.

3 Justification for Provisional Data Release

The USAF is leading the F7C2 space weather calibration and validation effort and is assisted by experts from the USAF, The Aerospace Corporation, Central Weather Bureau (CWB), Jet Propulsion Laboratory (JPL), National Cheng Kung University (NCKU), National Central University (NCU), National Oceanic and Atmospheric Administration (NOAA), National Space Organization (NSPO), and University Corporation for Atmospheric Research (UCAR). The team has worked intensively to evaluate instrument performance and optimize processing algorithms since launch. Metrics evaluated for this data release include colocation comparison of the relative TEC to determine the TGRS TEC precision, ionosonde fof2 daily comparison with TGRS electron density profile derived fof2, comparison of TGRS S4 values from the onboard algorithms vs those calculated based on high rate signal-to-noise ratio (SNR) data. Examples of initial results are shown in this document.

All TGRS instrument data in this release were collected with v4.3.2 or later flight software. The v4.3.2 software was uploaded to all flight instrument in late September 2019. This addressed issues related to reboots, occasional periods without data collection, and adjusted rising occultation tracking parameters.

1. Relative TEC data (podTc2 files)

   The precision of F7C2 relative TEC observations has been assessed through a comparison of collocated observations from early in the mission. Figures 1 and 2 are histograms of the GPS and GLONASS relative TEC difference between observation pairs from different LEO satellites to the same GPS or GLONASS PRN. The collocation criteria are 0.5^{o} in latitude and longitude, and 2 minutes temporally. The results in Figures 1 and 2 are based on observations for the time period 2019.200-220. Note that as these are relative TEC comparisons, we subtract the TEC at the initial epoch of the collocation from each observation.

   The results in Figures 1 and 2 illustrate the good precision of the F7C2 relative TEC observations for both GPS and GLONASS. Both distributions are centered near 0.0 TECU (mean of -0.01 TECU for GPS and 0.06 TECU for GLONASS). The standard deviations of the distributions are 0.13 TECU for GPS and 0.18 TECU for GLONASS. For comparison, Figure 3 is a histogram of differences in relative TEC for FORMOSAT-3/COSMIC-1 (F3C1) collocations for the period 2006.235-245. The mean and standard deviation of the F3C1 relative TEC differences are 0.002 TECU and 0.17 TECU, respectively. Based on Figures 1-3, the precision of the F7C2 relative TEC observations is better than that of F7C2 for GPS, and F7C2 GLONASS relative TEC observations have a precision similar to the precision of F3C1 observations.

2. Electron Density Profiles (ionPrf files)

   Data are obtained by inversion of calibrated TEC data, which are derived from the L1 and L2 signal phase differences and calibrated using two modes described in the CDAAC ionosphere algorithm description document. In this method, there is no DCB calculation. The phase corrections are based assumptions given in the document. Daily comparison between the electron density profile foF2 and ground-based ionosonde fof2 data showed very consistent scatter plots, some of which have correlation of 0.97. The method has been used for F3C1 data processing. Figure 4 shows two examples of the daily comparison, which demonstrate that the electron density profiles from F7C2 are consistent with the commonly used ground-based data and ready for public release. No biases have been found.

3. On-Board S4 Observations (podTc2 files)

   The TGRS sensor performs an on-board calculation of the S4 scintillation index (Equation 1 below) for each Global Navigation Satellite System (GNSS) satellite tracked by the precise orbit determination (POD) antennas. The calculation is performed at a 10s cadence based on underlying 50 Hz (GPS) or 100 Hz (GLONASS) SNR data. In the Eq. 1, the quantity P is the signal power, which proportional to the square of the voltage SNR reported by TGRS. The podTc2 files contain an unmodified copy of the on-board S4 calculation.

$$S4 = \sqrt{\frac{< P^2 > - < P >^2}{< P >^2}} \tag{1}$$

   The TGRS on-board S4 calculation has been validated by comparison to an independent S4 calculation based on high rate SNR data that is included in the TGRS telemetry. The on-board and independent calculations match to better than 4%. Qualitative review of S4 profiles obtained during the occulting portions of GNSS tracks has determined that the TGRS measurements are generally similar to the observations of prior radio occultation sensors (e.g., the CORISS instrument on C/NOFS). Based on the above, the on-board S4 products are considered ready for provisional public release.

4 Provisional Data Caveats

We note the following caveats to provisional data users:

- Relative TEC
  No DCB or multipath correction for the relative TEC products. UCAR is working on the DCB and multipath corrections for the absolute TEC, which is to be release at a later date. As such the relative TEC data contain biases from multiple sources and cannot be used for absolute determination of the slant TEC.

- On-Board S4
  Science data users should be aware that there are occasional data quality issues for the S4 data. Mostly these come in the form of anomalously high values at beginning of a GNSS track. Such observations, which are readily identifiable in time series plots, should be regarded as spurious. The F7C2 DPC has not yet implemented any quality control processes/flags to remove/identify such events.

  In addition, users should be aware that the GPS L2 S4 values for older GPS satellites (those that don't transmit the L2C code) are made based on SNR values obtained from semi-codeless tracking techniques. Because of this, they reflect signal fluctuations at both the L1 and L2 frequencies since semi-codeless processing depends on both of these signals. The L2 S4 values for newer GPS satellites (those that transmit L2C) and for GLONASS represent independent observations relative to the L1 S4 values.

5 Path Forward

The F7C2 team is working on several tasks:

- Reprocess mission data prior to October 1, 2019 in a manner consistent with this release, document features, and make available to the public.

- Continue to work on DCB and multipath-correction for the absolute TEC.

- Develop quality control software for the TGRS scintillation products.

We plan to release future provisional data approximately daily. Operational constraints may, however, cause occasional delays. If significant processing changes impacting product quality are made, we will increment the provisional release version, make the corresponding download area subdirectory, and provide release notes describing the changes.

IVM sensor data products from the different F7C2 satellites will be released on a staggered schedule. In-situ Ion Density products for all IVM sensors are currently scheduled for release at the end of April 2020. Ion Temperatures, Composition and Drifts will be released one satellite at a time over the 12 months that follow as validation work for each IVM completes and the F7C2 satellites are all lowered to their final altitudes.

F7C2 TGRS space weather initial operational capability is currently expected in November 2020. Upon reaching this milestone, all data and products will be released on a daily basis.

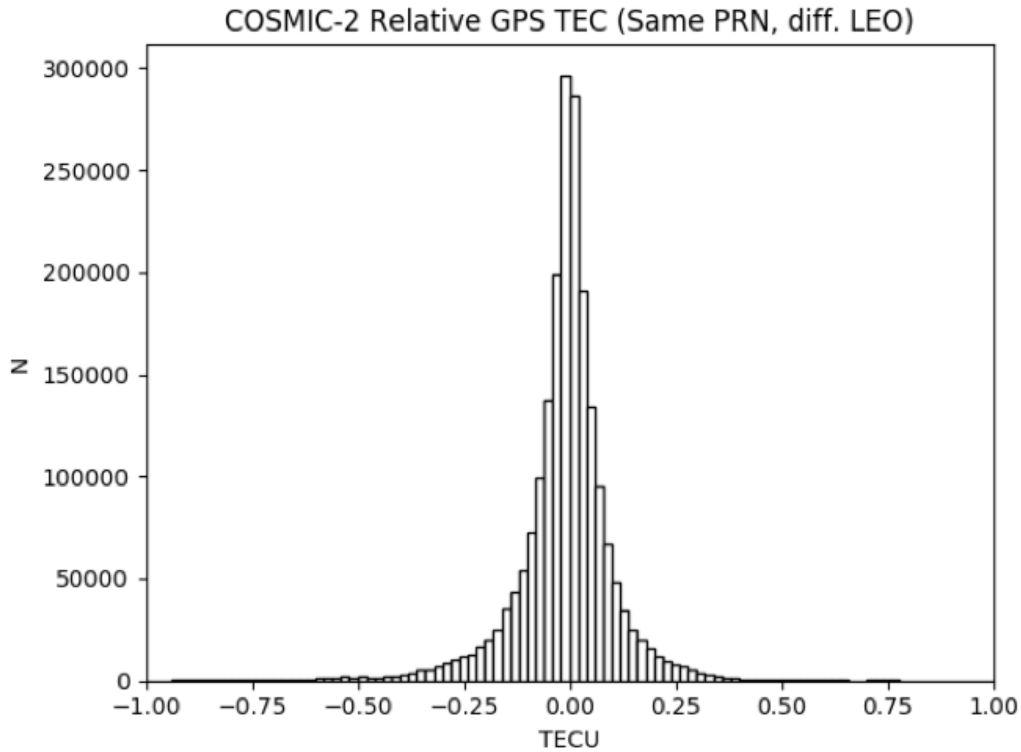

Figure 1: Histogram of the difference in relative TEC for collocated F7C2 GPS observations. Results are based on different LEO satellites observing the same GPS PRN.

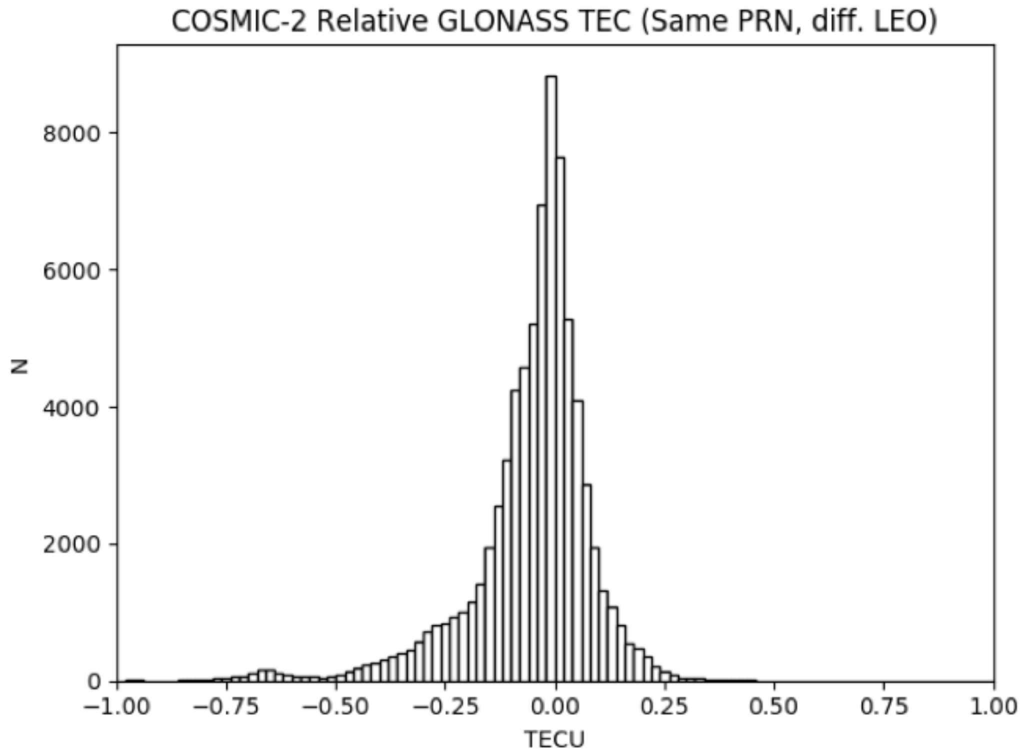

Figure 2: Histogram of the difference in relative TEC for collocated F7C2 GLONASS observations. Results are based on different LEO satellites observing the same GLONASS PRN.

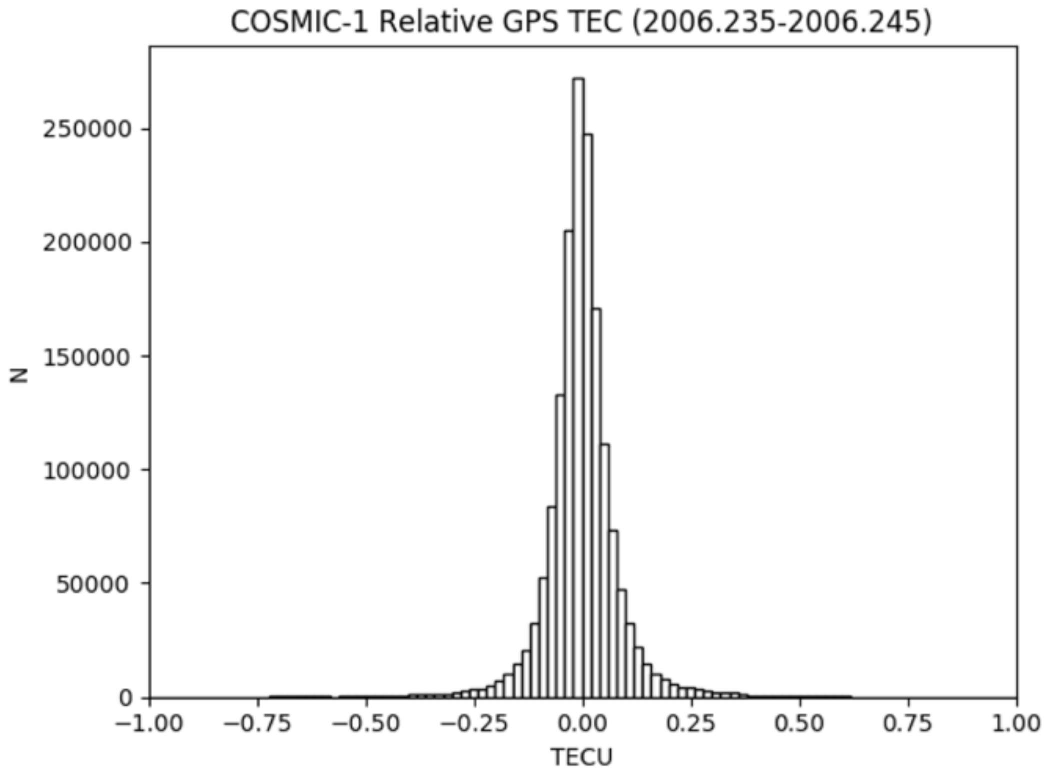

Figure 3: Histogram of the difference in relative TEC for collocated F3C1 observations. Results are based on different LEO satellites observing the same GPS PRN.

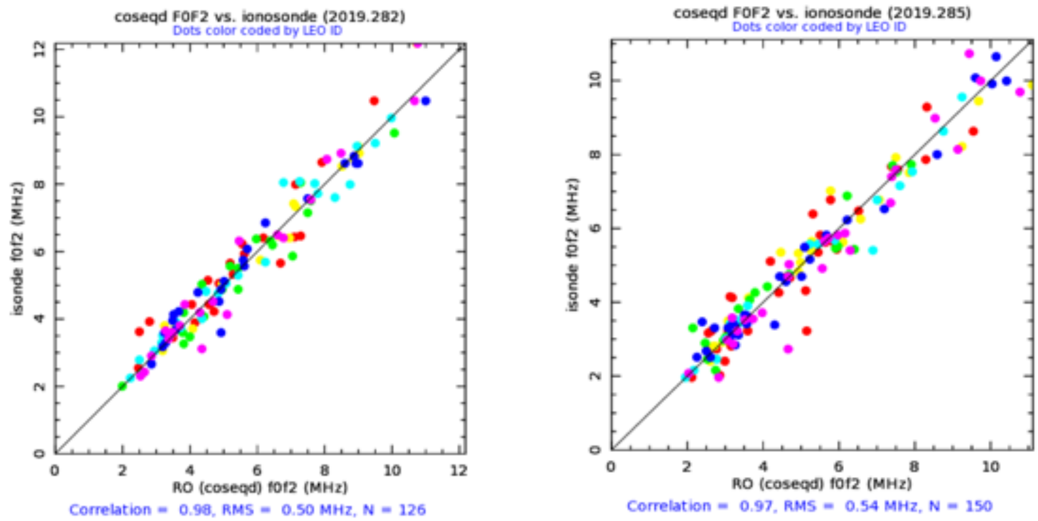

Figure 4: Two examples of daily ionosonde (vertical axis) fof2 vs F7C2 TGRS electron density profile derived fof2 (horizonal axis). Fof2 is related to the peak electron density. High correlation between the ionosonde and TGRS data provide good confidence to the TGRS electron density profile data.

6 Links

- F7C2 space weather provisional data download
  `https://data.cosmic.ucar.edu/gnss-ro/cosmic2/provisional/spaceWeather`
  `https://tacc.cwb.gov.tw/v2/download.html`
- COSMIC Data Analysis and Archive Center
  `https://cdaac-www.cosmic.ucar.edu/`
- Taiwan Analysis Center for COSMIC
  `https://tacc.cwb.gov.tw`
- CDAAC user support forum
  `https://groups.google.com/a/ucar.edu/forum/#!forum/cdaac-users`
- Algorithms for inverting radio occultation signals in the ionosphere
  `https://cdaac-www.cosmic.ucar.edu/cdaac/doc/documents/gmrion.pdf`
- podTc2 format
  `https://cdaac-www.cosmic.ucar.edu/cdaac/cgi_bin/fileFormats.cgi?type=podTc2`
  `https://tacc.cwb.gov.tw/cdaac/cgi_bin/fileFormats.cgi?type=podTc2`
- ionPrf format
  `https://cdaac-www.cosmic.ucar.edu/cdaac/cgi_bin/fileFormats.cgi?type=ionPrf`
  `https://tacc.cwb.gov.tw/cdaac/cgi_bin/fileFormats.cgi?type=ionPrf`

References

[1] Braun et al., *Performance of the FORMOSAT-7/COSMIC-2 Tri-GNSS Radio Occultation System (TGRS) Instrument During Early Oribt Operations for Space Weather Applications*, Fall AGU, San Francisco, USA, December, 2019.

[2] Straus et al., *Validation of COSMIC-2 Space Weather Science Products*, AMS Annual Meeting, USA, January, 2020.

Acronyms

CDAAC COSMIC Data Analysis and Archive Center

CWB Central Weather Bureau

F3C1 FORMOSAT-3/COSMIC-1

F7C2 FORMOSAT-7/COSMIC-2

GNSS Global Navigation Satellite System

IVM Ion Velocity Meter

JPL Jet Propulsion Laboratory

NCKU National Cheng Kung University

NCU National Central University

NOAA National Oceanic and Atmospheric Administration

NSPO National Space Organization

POD precise orbit determination

RFB Radio Frequency Beacon

RO radio occultation

SNR signal-to-noise ratio

TACC Taiwan Analysis Center for COSMIC

TEC total electron content

TGRS Tri-GNSS Radio-occultation System

UCAR University Corporation for Atmospheric Research

USAF United States Air Force