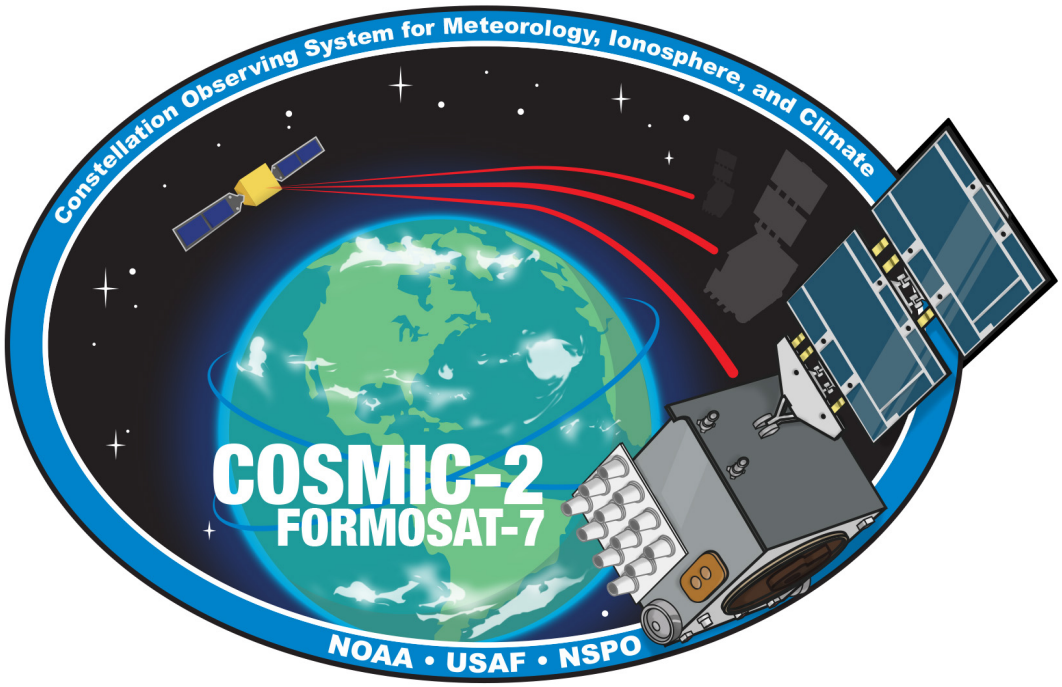
FORMOSAT-7/COSMIC-2
Space Weather Data Release 2

September 8, 2020



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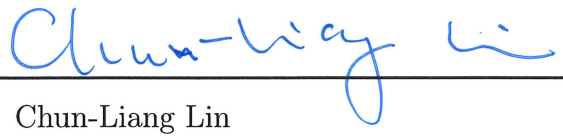

Dr. Chun-Liang Lin
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1 Background

The United States Air Force (USAF) Space Test Program 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. Each F7C2 satellite has three payloads. The primary instrument is the Tri-GNSS Radio-occultation System (TGRS) payload. Secondary instruments include the Ion Velocity Meter (IVM), and Radio Frequency Beacon (RFB) science payloads. Following spacecraft system activation and checkout, the primary and science payloads were first activated on July 16, 2019. This data release is focused on the absolute TEC derived from TGRS measurements of GPS satellite signals.

2 Summary of Data Release

The F7C2 space weather calibration and validation effort is lead by the USAF and assisted by experts from the USAF, The Aerospace Corporation (AERO), 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). Summaries of space weather early orbit and calibration and validation (Cal/Val) activities are described in [1] and [2]. The team has worked intensively to evaluate instrument performance and optimize processing algorithms since launch. This space weather data release includes the operational release of absolute GPS Total Electron Content (TEC). Release of data as operational indicates that the space weather Cal/Val team has verified that the data quality meets the operational requirements of both the USAF and NOAA. Aside from GPS TEC, the TGRS data products that were released provisionally beginning on March 30, 2020 remain unchanged. These provisional products are relative GLONASS TEC, the scintillation amplitude index (S4), and electron density profiles. The release of absolute GLONASS TEC is expected near the end of 2020. See section 6 for the data download locations and file format descriptions.

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.

3 Justification for Data Release

Release of data is based upon verification and validation of data quality through comparisons with independent truth measurements from the Swarm-B satellite.

3.1 Operational Data (GPS Absolute TEC)

Release of data as operational indicates that the space weather cal/val team has verified the data quality meets the operational requirements of both the USAF and NOAA. Specifically, the GPS absolute TEC has been shown to meet the Level 1 mission requirements of being accurate to better than 3 TECU.

1. Level 1b - GPS Absolute TEC data (podTc2 files)
   The accuracy of the absolute TEC data products has been shown to better than 3 TECU using independently verified Swarm-B TEC data products. Figure 1 shows a scatterplot of F7C2 absolute GPS TEC data and Swarm-B TEC. The criterion used to define a collocation measurement was a simultaneously observed measurement from both a F7C2 and Swarm-B satellite with less than 2^o latitude and longitude separation. Since the Swarm-B and F7C2 satellites orbit at slightly different altitudes, the Swarm-B TEC observations have been adjusted to the F7C2 altitude using the IRI-Plas model. The comparison between these two data sets provided an accuracy assessment of F7C2 data that satisfied the mission requirements of less than 3 TECU. Comparisons were made using F7C2 satellites FM1, FM2, and FM4, which are all near the final orbit altitude of 550 km.

3.2 Provisional Data (Unchanged from March 30, 2020 Release)

Metrics use to evaluate provisional data products include a 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 SNR data. Examples of initial results are shown in this document.

1. Level 1b - GLONASS 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 2 and 3 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° in latitude and longitude, and 2 minutes temporally. The results in Figures 2 and 3 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 2 and 3 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 4 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 this analysis,, 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. level 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 on assumptions given in the document. Daily comparison between the electron density profile foF2 and ground-based ionosonde fof2 data showed consistent scatter plots, some of which have correlation of 0.97. The method has been previously used for F3C1 data processing. Figure 5 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 significant biases have been found.

3. level 1b - On-Board S4 Observations (podTc2 files)

   The TGRS sensor performs an on-board calculation of the S4 scintillation index (Equation 1 below) for each GNSS satellite tracked by the 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 is 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 Data Caveats

Absolute GPS TEC from after October 1, 2019 are included in this release. Relative GLONASS TEC, S4, and electron density profiles are provided on a provisional basis. This start date of October 1, 2019 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. We note the following caveats to data users:

- GPS Absolute TEC
  Only GPS TEC data products are provided as absolute measurements.

- GLONASS Relative TEC
  The GLONASS TEC data products do not include GLONASS DCB estimates or multipath corrections. UCAR is working on the DCB and multipath corrections as part of the absolute TEC processing system, and will release these data products 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. Most of these come in the form of anomalously high values at the 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 Space Weather Cal/Val team is working on developing validating TGRS GLONASS absolute TEC from observations, including DCB estimation. This operational release currently targeted for December 2020. The Cal/Val team is also working to develop and evaluate TGRS scintillation data products and associated quality control software. Operational release of a quality-controlled version of the on-board S4 product is currently planned for December 2020. Provisional release of the TGRS ionospheric high rate data and associated phase scintillation product is currently planned for March 2021.

The release of IVM sensor in-situ density products has been delayed due to COVID-19 impacts that have prevented timely ground truth data collection. The Cal/Val team is currently targeting November 2020 for release of these products. Provisional release of IVM ion drifts from FM1, FM2 and FM4 are also expected in November 2020. An updated provision release of improved IVM ion drifts for these satellites plus FM3 is expected in March 2021. All remaining IVM products are planned for operational release in June 2021.

All data space weather products described in this memo are expected to be released daily. Operational constraints may, however, cause occasional delays. While not anticipated, if significant processing changes impacting product quality are made, we will increment the release version, make a corresponding data download area subdirectory, and provide release notes describing the changes.

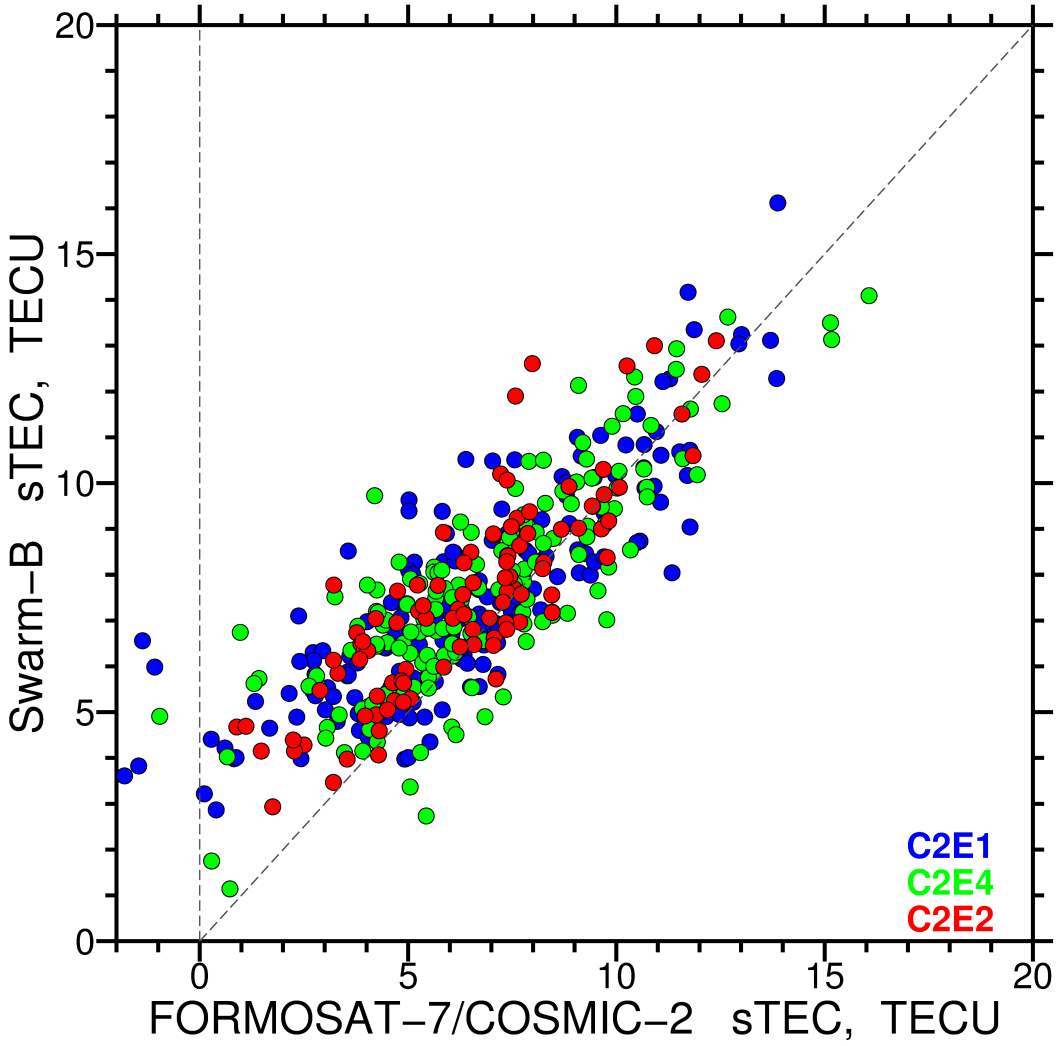

Figure 1: Scatterplot of GPS TEC with collocated measurements from the Swarm-B satellite. Results from LEO satellites FM1, FM2, and FM4 are shown.

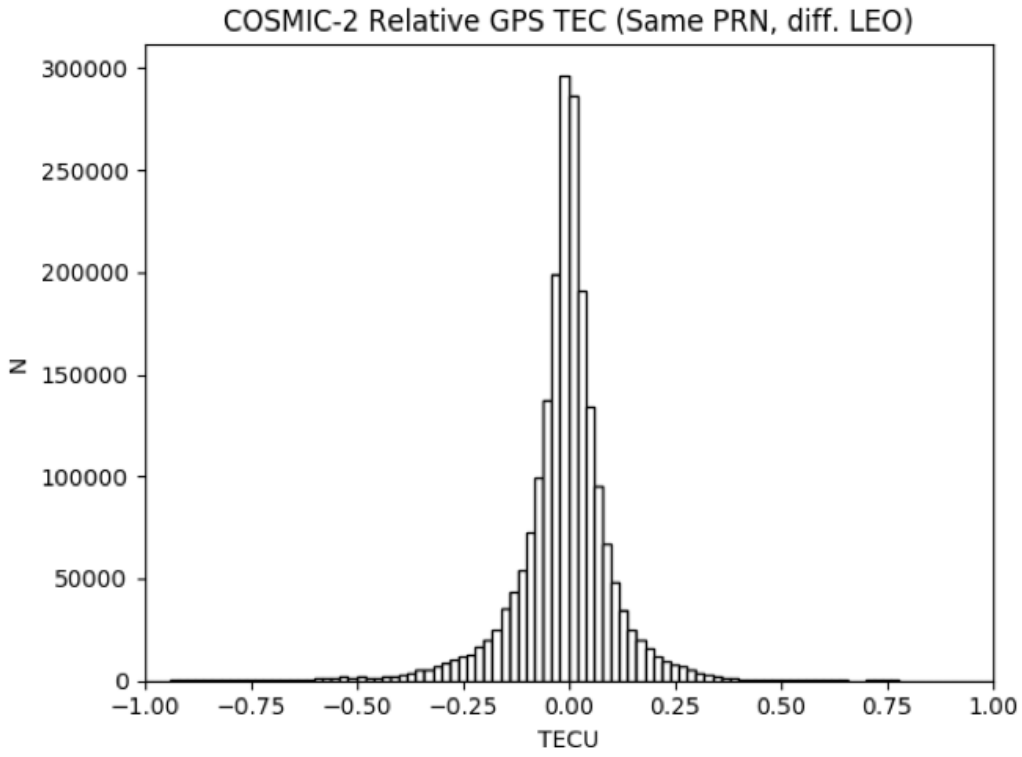

Figure 2: Histogram of the difference in relative TEC for collocated F7C2 GPS observations. Results are based on different LEO satellites observing the same GPS PRN.

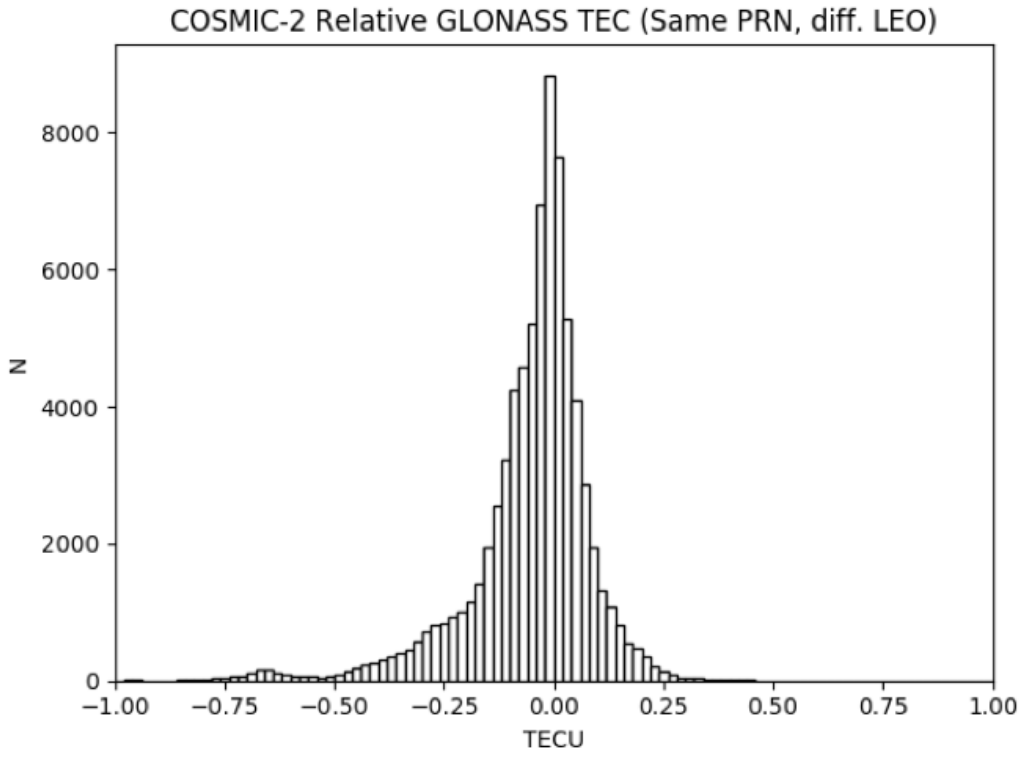

Figure 3: Histogram of the difference in relative TEC for collocated F7C2 GLONASS observations. Results are based on different LEO satellites observing the same GLONASS PRN.

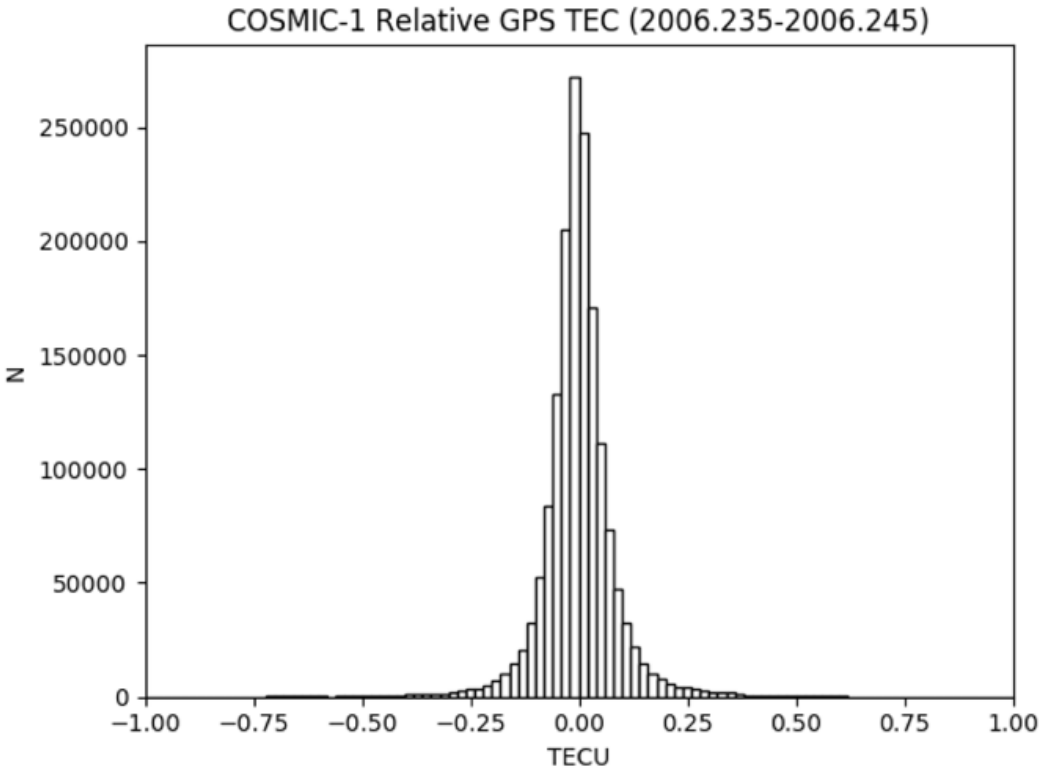

Figure 4: Histogram of the difference in relative TEC for collocated F3C1 observations. Results are based on different LEO satellites observing the same GPS PRN.

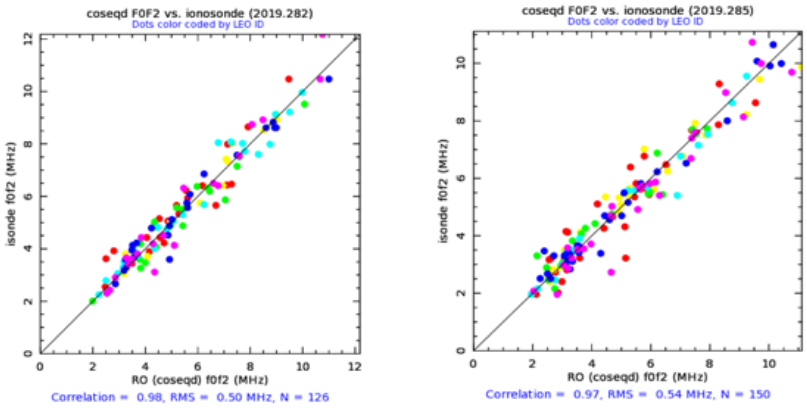

Figure 5: Two examples of daily ionosonde (vertical axis) fof2 vs F7C2 TGRS electron density profile derived fof2 (horizonal axis). Fof2 is related to the peak electron density. High correlation between the ionosonde and TGRS data provide good confidence to the TGRS electron density profile data.

6 Links

- F7C2 space weather provisional data download
  `https://data.cosmic.ucar.edu/gnss-ro/cosmic2/provisional`
  `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.