Radio Occultation and access to COSMIC data

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OUTLINE

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**GNSS RADIO OCCULTATION (RO)**

- Atmospheric probing by GNSS radio occultation (RO) measurements on board Low Earth Orbiting (LEO) satellites is a powerful technique for monitoring the vertical structure of the ionosphere and therefore to collect information on key ionospheric characteristics covering areas of the globe such as oceans where ground instrumentation such as GNSS receivers and radars are impossible to operate.

- Convincing evidence of the effective ionospheric sounding via RO was initially demonstrated through the GPS-Met experiment onboard Microlab-1 and further by following LEO missions such as CHAMP, GRACE, SAC-C, F3/C and C/NOFS.

- Based on extended RO datasets the accuracy and reliability of this technique has been questioned and contradicted against ground based techniques and was established as a complementary technique posing its extended spatial coverage as its main advantage.
DAILY RO EVENTS OF CHAMP, GRACE AND FORMOSAT3/COSMIC MISSIONS
FORMOSAT-3/COSMIC

• The most successful mission in terms of its ionospheric related research potential is the F3/C which provided around 2500 RO per day at its operational peak in 2009 facilitating a significant number of ionospheric studies. Currently this pioneering mission is on its final operational stages with remaining operating satellites at a reduced altitude collecting less than 500 ROs per day. Numerous ionospheric studies have been performed on the extended dataset of more than 4 million ionospheric RO collected by the six satellites of F3/C since 2006.

• Of particular interest are the comparisons with ionosonde peak ionospheric characteristics and bottomside profiles and full vertical profiles with incoherent scatter radars of collocated RO observations that served as a means to validate the RO technique under certain assumptions and data quality conditions over a limited geographical scale. In fact since the RO EDP is the result of two moving satellites the actual tangent point during the RO event moves significantly in the horizontal direction on the order of several hundred km. This is the main reason that certain azimuthal orientations (particularly NS and especially at low latitudes) would result in increased error as the bottomside or topside ionosphere varies significantly from the vertical at the collocated NmF2-hmF2 point (normally <2-3 degrees) under these circumstances.
FORMOSAT-3/COSMIC
Constellation Observing System for Meteorology, Ionosphere, and Climate

• 6 Satellites launched in 2006

• Orbits:
  altitude=800km, Inclination=72deg

• Weather + Space Weather data

• Global observations of:
  - Refractivity
  - Pressure, Temperature, Humidity
  - Total Electron Content TEC
  - Ionospheric Electron Density
  - Ionospheric Scintillation

• Global coverage in near-real time for
  - Climate Monitoring
  - Geodetic Research

COSMIC Radio Occultation profiles
from COSMIC Data Analysis and Archive Center (CDAAC)
(http://tacc.cwb.gov.tw/cdaac/index.html)

Will provide instructions for data download
EXAMPLES OF RO MEASUREMENTS
Each COSMIC satellite is equipped with two antennas, which are used for ionospheric electron density measurements (one for rising and one for setting occultations). These antennas collect L1 and L2 GPS phase data from up to 13 GPS satellites every second. The inversion of COSMIC data into electron density profiles is based on the difference between L1 and L2 GPS phase path measurements. This is based on the bending angle ($\alpha$) of GPS ray received by the GPS receivers that exist on LEO satellites, which can be converted into atmospheric refractive index through the Abel transformation. This refractive index allows for the reconstruction of the electron density and scintillation in the ionosphere, as well as the pressure, temperature and humidity in the neutral atmosphere.
Illustration of the idea of spherical symmetry used in the standard Abel inversion.
COSMIC SOUNDINGS IN 1 DAY

Green points: Occultation locations for COSMIC, 6 satellites, 24 hours
Red points: Radiosonde locations
SPECIFIC HUMIDITY OVER CYPRUS

1st March 2007, 17:00 local time
GNSS RADIO OCCULTATION (RO)

• The new upcoming RO mission F7/C2 comprising of 6 LEO satellites that was deployed in June 2019 will overcome the main limitation of earlier missions which was the insufficient spatial and temporal resolution to resolve short time scale ionospheric signatures. F7/C2 satellites will achieve this goal by receiving signals from three GNSS systems (GPS, Glonass, Galileo) and were planned to record nearly 12,000 occultation events per day which is about 4 times more than that provided by the previous F3/C mission. Unfortunately, the second cluster of F7/C2 satellites in high-inclination orbits, COSMIC 2B that had been planned for a launch was cancelled in October 2017 due to a lack of funding.
• As demonstrated by simulations even without the 2B segment the F7/C2 RO events will approximately cover the entire globe and will possibly resolve signatures with time scales longer than an hour, such as atmospheric tidal effects, solar flux influences, and geomagnetic disturbances using 1–2 h of data. This will be a significant improvement over the F3/C, which was unable to study daily behavior of the ionosphere at any specific point due to lack of recurrent observations over a certain location. The global 3-D ionospheric electron density structure could only be obtained with F3/C by binning data accumulated over long periods of up to more than a month.
Comparison between (a) FORMOSAT-3/COSMIC and (b) FORMOSAT-7/COSMIC-2 in (left) constellation, (middle) RO events during 3 h, and (right) key parameters.
FORMOSAT-3/COSMIC past studies

- More extended regional and also global studies have also been performed demonstrating also how peak characteristic (NmF2-hmF2) discrepancy between ionosonde and RO EDP varies with collocation distance. The main findings of these studies were a systematic overestimation of ionosonde peak height hmF2 and an underestimation of electron density NmF2 characteristics and a latitude dependent degree of these discrepancies. These differences were attributed to non-validity of the assumption for spherical symmetry for the Abel inversion which implies that no horizontal gradient of the refractive index exists along the spherical shell. These uncertainties in the estimation of EDP is also due to noisy EDPs due to excessive irregularities especially in low latitude regions and also at low altitudes therefore increasing the uncertainty in extracting bottomside and E-region EDP information.

from Chu et al., 2010
A comparison of the global distributions of the monthly averaged peak electron densities between COSMIC data (left panels) and IRI model predictions (right panels). from Yang et al., 2007
FORMOSAT-3/COSMIC past studies

Daily RMS of the retrieved peak density NmF2 (left) and corresponding height hmF2 (right) derived from radio occultations between 10 June 2006 and 29 April 2014.

from Limberger et al., 2015
The ionospheric midlatitude trough observed by FORMOSAT-3/COSMIC during solar minimum.

from Lee et al., 2011
FORMOSAT-3/COSMIC

- The presence of density irregularities can also produce unrealistic negative EDPs but could also lead to scintillation and multipath effects that often give rise to highly fluctuating and random EDPs therefore reliable data quality control measures have been proposed to screen these EDPs for further consideration. The uncertainties introduced by the weaknesses of classical Abel inversion have encouraged researchers to propose recommendations and techniques for improvement by incorporating background electron density information either in terms of modeled or estimated (in terms of maps) Total Electron Content (TEC).
GNSS RADIO OCCULTATION (RO)

• In addition to EDP mapping on a local, regional or global scale the instrumentation on board RO satellites has facilitated mapping of F-region and E-region irregularities. Through seasonal averaging of CHAMP scintillation measurements or even monthly averaging in the case of F3/C, the global morphology of spread F was investigated at a remarkable spatial resolution revealing noticeable features. The sporadic E morphology and climatology was also demonstrated on a global scale exposing the tidal and geomagnetic field control of intermediate descending layers which give rise to sporadic E layers in accordance to the well-known wind shear theory. Through RO missions it was also possible to examine the morphology of various ionospheric characteristics on a global scale and validate models through their estimated median behaviour such as International Reference Ionosphere (IRI) and NeQuick. It also enabled the scientific community to visualize in unprecedented spatial detail phenomena such as the mid-latitude trough (MLT), Weddell Sea Anomaly (WSA) and South Atlantic Anomaly (SAA).
GLOBAL WINDSHEAR MECHANISMS OF Es FORMATION AS SEEN BY RO

(Arras et al., 2008)
Examples of EDPs over Cyprus at different hours.

Temporal and spatial characteristics of EDP
Examples of EDPs at noon over Cyprus at different solar activity conditions.
Temporal and spatial characteristics of EDP
Temporal and spatial characteristics of EDP

Seasonal variation of foF2 at noon at low, medium and high latitudes.
Electron density $N_e$ (el/m$^3$)

Altitude (km)

IRI driven by foF2_hmF2
IRI
COSMIC
Measurement of electron density by ground-based and satellite techniques
CHOOSING A DATASET FOR TOPSIDE VALIDATION

When the RO-derived electron density peak and height match the true peak values, the full topside Ne(h)-profile may be considered accurate. In order to validate this hypothesis with experimental data, electron density profiles obtained from four different incoherent scatter radars have therefore been considered together with co-located RO-derived Ne(h)-profiles. The evidence presented in this paper show that in all cases examined, if the incoherent scatter radar and the corresponding co-located RO profile have matching peak parameter values, their topsides are in very good agreement (M. M. Shaikh et. Al. JGR 2018).

<table>
<thead>
<tr>
<th>Table 1</th>
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<tbody>
<tr>
<td>Number of Co-located Ne(h)-Profiles at Each ISR Site</td>
</tr>
<tr>
<td>ISR</td>
</tr>
<tr>
<td>---------</td>
</tr>
<tr>
<td>Arecibo</td>
</tr>
<tr>
<td>Jicamarca</td>
</tr>
<tr>
<td>Milestone Hill</td>
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<tr>
<td>Poker Flat</td>
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CHOOSING A DATASET FOR TOPSIDE VALIDATION

The ionosonde and COSMIC profiles in these examples were obtained over Cyprus. These particular ionosonde and COSMIC profiles were selected so that their peak electron density and corresponding altitude only differed by less than 5%. In this way we could ensure very good quality profiles in the topside investigation since they were measured by two independent techniques in such a good agreement.

All the pairs of FORMOSAT3/COSMIC foF2 and hmF2-Cyprus Digisonde foF2 and hmF2 and those within 5% difference in the period 2009-2012.
RADIO OCCULTATION MEASUREMENTS OVER CYPRUS FOR TOPSIDE VALIDATION
2009

Electron density ($10^5 \text{el cm}^{-3}$)

Altitude (km)

COSMIC Ionosonde

Electron density ($10^5 \text{el cm}^{-3}$)

Altitude (km)

COSMIC Ionosonde
Electron density ($10^5$ el cm$^{-3}$) vs. Altitude (km) for 2010.

- Red line: COSMIC
- Black line: Ionosonde

[Graph showing electron density for COSMIC and Ionosonde over the years 2010.]

Nicosia, N1135
2010.09.23 14:16:00.000

[Weather patterns and conditions represented in the graph for Nicosia, N1135 on 2010.09.23 at 14:16:00.000.]

S/A/E: Explorer, v 3.4.19b1
COSMIC, Ionosonde and IRI topside electron density profiles over Cyprus
The average behaviour of IRI clearly represents the COSMIC measured behaviour encapsulating the expected annual variation.
Difference between COSMIC and IRI foF2 for 2010 over the investigation region

A more detailed examination of the discrepancy between COSMIC and IRI foF2 values reveals maximum deviation during equinox months.
The figures below demonstrate the presence of a high electron density patch at around 100 km obstructing any usable reflections above this altitude as shown in the corresponding ionogram obtained by the ionosonde at the same approximate time interval.
Matched CPSMIC-DIGISONDE EDPs over Cyprus

Matched EDPs over Cyprus with (a) good match in foF2 and hmF2 (b) good match in foF2 and slight mismatch in hmF2 (c) mismatch in foF2 and good match in hmF2 (d) mismatch in both foF2 and hmF2.
Matched EDPs over Cyprus around sunset exhibiting significant mismatch
Radio occultation measurements
The DIAS system

- DIAS integrates in the same environment all raw ionospheric data gathered by DIAS ionospheric stations geographically distributed over Europe with the capability of automatically scaling and transmitting in real time all important ionospheric parameters.

- The knowledge on the state of the ionosphere generated by each ionosonde is valid only for a limited area around each station.

- DIAS calculates the topside electron density profile over each ionospheric station assuming an $\alpha$-Chapman function with constant scale height $HT$ (derived from bottomside ionograms) for the topside electron density distribution.
The DIAS system

Ionospheric stations contributing data to DIAS
Occultation event in the vicinity of three Digisonde stations over Europe. (Krankowski et al 2011).
The DIAS system

Example of Electron Density profiles at all DIAS Ionospheric European stations produced by DIAS
Outliers in the comparison can be caused by unsuccessful automatic determination of foF2 under inhomogeneous ionospheric conditions.
Data selection methodology

Or by the inability of the inversion of the radio-occultation into a realistic profile
Validation Ionosonde DIAS vs COSMIC

- Rome foF2 values DIAS vs COSMIC
- Arenosillo foF2 values DIAS vs COSMIC
- Athens foF2 values DIAS vs COSMIC
- Ebre foF2 values DIAS vs COSMIC
- Chilton foF2 values DIAS vs COSMIC
- Julkusruh foF2 values DIAS vs COSMIC
- Pruhonice foF2 values DIAS vs COSMIC
- Moscow foF2 values DIAS vs COSMIC
Results

Electron density (el cm$^{-3}$) vs. Altitude (km)

- --- Ionosonde
- ---- COSMIC
- --- IRI

**a)** Juliusruh  25/10/2008 16:37 UT
**b)** Juliusruh  30/6/2009 03:11 UT
**c)** Juliusruh  7/5/2009 09:24 UT
**d)** Juliusruh  21/9/2009 16:10 UT
Results

a) 4/10/2006 17:08 UT

b) 24/2/2007 22:52 UT
Example of a nowcasting map for foF2 over Europe produced by DIAS
In total, 51387 foF2 values were used in the comparison of COSMIC and DIAS values in this investigation.

We selected values of COSMIC occultations with the measurement of foF2 at the approximate time of the DIAS maps which are provided by the system every 15 minutes.

Also due to the fact that the DIAS system provides maps of foF2 at 1° resolution, the COSMIC measurements with foF2 values were selected in close proximity to DIAS measurements.

To match a COSMIC measurement with a DIAS map point there should be a difference of less than 7 minutes and 0.5°.
Data

- Missing DIAS maps were primarily due to the lack of sufficient DIAS stations that could contribute to the generation of a map.

- The foF2 values were extracted from ASCII files of nowcasting foF2 maps over the European area produced by the DIAS system.

- These maps are generated by the real-time updating of the Simplified Ionospheric Regional Model (SIRMUP) based on auto-scaled ionospheric parameters measured by DIAS ionosondes.
Plots describing the relative error percentage between DIAS and COSMIC for 2008 expressed as (a) contours over Europe (b) scatter plots (c) histograms
DIAS-COSMIC comparison

- It is clearly evident that there is a correlation between DIAS foF2 nowcasting and COSMIC.

- It can also be inferred from the histograms that in general DIAS tends to slightly underestimate the COSMIC values.

- The most interesting feature comes out of the spatial characteristics of the relative error between DIAS and COSMIC. These diagrams demonstrate that there is a definite latitude dependence of the relative error with a clear underestimation of COSMIC measurements at high latitudes and overestimation at European low latitudes.

- The best approximation to COSMIC measurements is at middle European latitudes due to decreased ionospheric variability and because of the fact that most ionosondes of DIAS system operating in this region, providing better coverage and as a result a more accurate ionospheric representation.

- The underestimation at high latitudes is expected taking into account the high ionospheric variability in this region combined with the limited ionosonde coverage.
COSMIC IONOSPHERIC INVESTIGATION OVER BANGLADESH

• To investigate the ionosphere over Bangladesh for the first time considering observations measured by satellite radio occultation (RO) missions.
• In absence of systematic ionosonde measurements over this area, RO measurements provide an opportunity to perform such a study by for years 2003-2015 with a limited dataset.
• We present a comparison of the peak ionospheric characteristics (foF2-hmF2) and electron density profiles (EDP) from the measured observations with International Reference Ionosphere (IRI-2012) model.
• Ionospheric irregularities have also been studied with COSMIC scintillation dataset during 2007-2014 and diurnal, seasonal, and long-term variation is reported.
COSMIC IONOSPHERIC INVESTIGATION OVER BANGLADESH

• Ionospheric Techniques-Models
  • Radio Occultation Missions
  • International Reference Ionosphere

• Ionospheric Irregularities
  • E-Layer irregularities
  • F-Layer irregularities

• Results
  • Peak Ionospheric Characteristics Comparison
  • Observations on E-Layer irregularities over Bangladesh
  • Observations on F-Layer irregularities over Bangladesh
Comparison of COSMIC and IRI electron density profiles over Bangladesh

![Graph showing comparison of COSMIC and IRI electron density profiles over Bangladesh.](image-url)
Comparison of COSMIC and IRI electron density profiles over Bangladesh

Scatter plot of COSMIC vs. IRI $foF2$ values

Scatter plot of COSMIC vs. IRI $hmF2$ values
Electron density profile over Bangladesh with a clear Es signature.
Variation of Scintillation with Altitude over Bangladesh

Altitudes below 120 km exhibit maximum scintillation, is in the E region, attributed to the presence of sporadic E.

Altitudes between 120 and 400 km correspond to the ionospheric irregularities in the lower F-region.
E-layer Scintillation (Annual Variation) over Bangladesh

Sporadic-E is quite systematic over Bangladesh with a high occurrence during the summer. (typical behaviour reported over the northern hemisphere in other studies).
Highest percentage occurrence of scintillations is observed for the **equinox months** and lowest is observed for **summer**.
F-layer Scintillation (Diurnal Variation) over Bangladesh

- Scintillation peaks several hours after dusk, around 1400 UT (2000 LT).
- Scintillation activity is most severe and frequent in and around the equatorial regions.
- Particularly just after sunset when small scale F-layer irregularities due to the Rayleigh-Taylor gravitational instability processes operating on the steep upward gradient in the bottom side F-region.
The long-term amplitude scintillation in the F-region shows a distinct increasing trend as the solar activity maximises in the period 2013-2014. This is again expected taking into account the location of Bangladesh with respect to the geomagnetic equator and the high scintillation levels at this region of the globe.