Multi-technique characterization of ionospheric Space Weather effects

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Prof. S. K. Mitra was one of the first in the world to suggest use of HF atmospheric radars with his observations in 1935.

The first experimental evidence of E layer predicted by Heaviside and Kennely was obtained by Mitra and Rakshit in 1930.

His seminal book 'The Upper Atmosphere' has been considered a Bible for researchers in the field.
This Department was the First in India to start Post-Graduate teaching in Electronics

The Ionosphere Field Station was established in 1953 at Haringhata, about 50km north-east of Calcutta at a place of relatively low radio frequency interference.

Professor Mitra assembled the First manual Ionospheric Sounding System in Asia in 1954 and established it at the Ionospheric Field Station in 1956 thereby putting University of Calcutta in an elite global chain of Ionospheric Sounders.

NBS-C2 Ionosonde data for the period 1957-1976 from Ionosphere Field Station at Haringhata available at the Space Physics Interactive Data Resources (SPIDR) website under the National Geophysical Data Center located at Boulder, Colorado, USA
SPACE SITUATIONAL AWARENESS

SPACE ENVIRONMENT S&T CHALLENGES (1)

SOLAR
- Solar energetic particle event specification & forecast
- Solar irradiance forecast
- Solar magnetic field specification & forecast

MAGNETOSPHERE
- Auroral oval specification & forecast
- Outer zone radiation belt specification & forecast
- Plasma specification & forecast

IONOSPHERE / THERMOSPHERE
- EUV-driven ionosphere/thermosphere coupled model
- Bottom-side specification & forecast (medium & large scale irregularities)
- Small-scale irregularity specification & forecast
- Profile specification & forecast
- Polar plasma specification
Near Earth Space Environment
Geostationary Neighbourhood

The orbit plane of a GEO satellite which ceases inclination control will evolve to a maximum inclination of 15° after 27 years and then return to the GEO belt after 53 years (nearly 55 years for 600km above GEO. This is caused by solar and lunar gravitational perturbations on the orbit plane.

Plot shows the inclination vectors of near GEO objects from Space-Track Catalogue as of July 2017. Satellites which stopped inclination control are starting to return to the GEO belt (credit Oltrogge AGI 2017)

Over the next decade 2020-2030 GEO satellites which were deorbited /abandoned in 1966-1976 will start to return to the GEO belt altering the makeup of the GEO debris population

The relative encounter velocities between controlled GEO satellites and uncontrolled satellites originating from GEO can be as high as 800 m/s for the maximum inclination of 15°.
Space systems and services operate in and through the natural space environment, so to have complete space situational awareness, we need to understand the natural space environment, for example:

- Solar particle and electromagnetic radiation
- Interplanetary phenomenon--e.g. CMEs, Coronal holes
- Magnetospheric radiation, fields, and currents
- Upper atmospheric density, temperature and winds
- Ionospheric density
- Galactic cosmic radiation
- Meteors

We need to understand the environment’s effects on space systems and services
SCINDA (SCIntillation Network Decision Aid) station of the US Air Force since November 2006 at the Institute of Radio Physics and Electronics, University of Calcutta, Calcutta
Multi-technique characterization of near-Earth Space Environment

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http://www.issibern.ch/teams/mtconese/
Ionospheric Space Weather effects pose a major challenge to reliable GNSS based operations even after extensive research globally.

Occurrence of spread-F, ionospheric TEC gradients and scintillations significantly perturb the performance of transionospheric satellite-based communication and navigation systems which may pose life-critical conditions, particularly for high dynamic platforms like aircrafts and adversely affect different strata of modern society.

In terms of the intensity of ionospheric propagation effects, the polar and equatorial regions provide worst-case scenario and results obtained in these regions serve as a benchmark for the international Space Weather community.

Interestingly, at equatorial and low latitudes, impact of ionospheric irregularities occurs even under geomagnetic benign conditions.

The scope of this work encompasses scientific inputs to advance the present understanding of Space Weather generated perturbations on technological systems.
In the present program, efforts are being made to achieve the following objectives:

1. i.) Comparison of the thermosphere-ionosphere effects of St. Patrick day storms of 2013 and 2015 over Europe, ii) effects of the geomagnetic storm of September 2017 over Europe, South-East Asia as well as Brazilian longitudes iii) effects of Joule heating and composition changes observed during intense geomagnetic storms of 2015-2017

2. Satellite signal outages observed from a network of stations distributed over low latitudes, mid latitudes and polar region within a longitude swath during periods of scintillations to check conformity with ICAO specified requirements for APV

3. Identify and characterize definitive condition for enhancement or inhibition of scintillation activities corresponding to intense geomagnetic storms. There are plans to develop long-term statistics for the low latitudes focussing on the geophysically sensitive Indian longitude sector
Comparison of the thermosphere-ionosphere effects of St. Patrick day storm of 2013 and 2015 over Europe
Geomagnetic conditions during the St. Patrick magnetic storms on 16–19 March 2015 (left panel) and 15–19 March 2013 (right panel). It is shown: (a) Solar wind speed, (b) Solar wind pressure, (c) total magnitude B of IMF (d) Bz component of IMF, (e) Dst ring current index, and (f) AE auroral electrojet index. The green vertical line represents the time of sudden storm commencement and the blue and red vertical lines indicate the 1st and 2nd Dst index minima respectively.

The geomagnetic storms on 17 March 2013 and 2015 present similar features though they exhibit different intensities. They were both induced by a Coronal Mass Ejection (CME) and commenced at approximately the same time (5 UT). Their main phase peaked at the same time (21-22 UT) and was marked with two minima of the Dst ring current index which occurred at almost same moments (around 10 and 22 UT).
Haralambous et al., J. Geophys. Res., 2019 (under review)
Temporal variations of ionospheric F region characteristics

16-17 March 2013

Temporal variations of ionospheric F region characteristics foF2 (upper panel), hmF2 (middle panel) and TEC (lower panel) in Fairford, Dourbes, Juliusruh, Pruhonice, Moscow, El Arenosillo, Ebre, Rome, San Vito and Athens stations during 16-17 March 2013. Green solid lines represent the quiet reference day (16 March) and red and blue solid lines represent storm variations on 17 and 18 March respectively. Light blue vertical lines denote the sudden storm commencement time (5 UT) and the time of 1st and 2nd successive Dst index minima (10 and 21 UT) in 17 March 2013.

Haralambous et al., J. Geophys. Res., 2019 (under review)
Temporal variations of ionospheric F region characteristics

Temporal variations of ionospheric F region characteristics foF2 (upper panel), hmF2 (middle panel) and TEC (lower panel) in Fairford, Dourbes, Juliusruh, Pruhonice, Moscow, Ebre, Rome, San Vito and Athens stations during 16-17 March 2015. Green solid lines represent the quiet reference day (16 March) and red and blue solid lines represent storm variations on 17 and 18 March respectively. Light blue vertical lines denote the sudden storm commencement time (04:45 UT) and the time of 1st and 2nd successive Dst index minima (10 UT and 22:45 UT) in 17 March 2015.

Haralambous et al., J. Geophys. Res., 2019 (under review)
TEC over Europe - day to day effect

16 to 18 March 2013, 12:30 UT

16 to 18 March 2015, 12:30 UT

INGV TEC plots confirming MIDAS maps

17 March 2013, 22UT

INGV TEC plots

MIDAS TEC maps

17 March 2015, 23UT

MIDAS TEC maps

INGV TEC plots

Haralambous et al., J. Geophys. Res., 2019 (under review)
TEC over Europe demonstrating TEC mid-latitude trough migration towards south

17 March 2013, 19-23 UT

17 March 2015, 19-23 UT

Haralambous et al., J. Geophys. Res., 2019 (under review)
Spread F phenomena in March 2013 storm event

17 March 2013,
18:00, 18:30, 19:30 UT

17 March 2013,
21:15, 21:30, 21:45 UT

Haralambous et al., J. Geophys. Res., 2019 (under review)
Spread F phenomena in March 2015 storm event

17 March 2015, 15:45, 16:15, 17:00 UT

17 March 2015, 17:45, 18:30, 19:00 UT

Haralambous et al., J. Geophys. Res., 2019 (under review)
F-region 15 min skymaps recorded on a) March 17, 2013 (21:45 to 22:30 UT) in right panel, and b) March 17, 2015 (20:45 to 22:30 UT) in left panel over Juliusruh station show horizontal location of reflection points. Values of Doppler shifts are distinguished by different colors.

**Athens 17 March 2015**

**Vz - Vnorth - Veast (m/s)**
- Quite average Vz
- Real Vz observations
Vz - Vnorth - Veast (m/s)

- Quite average Vz
- Vz observations

Fairford, 17 March 2013
Fairford, 17 March 2015
Juliusruh, 17 March 2013
Juliusruh, 17 March 2015

TID signatures

Strong westward plasma motion

Strong westward plasma motion
Effects of the geomagnetic storm of September 2017 over Europe, South-East Asia as well as Brazilian longitudes
Geomagnetic conditions

The storm event of September 7–8, 2017, is a rare event because:

a) It is not one storm with two-step main phase, but it consists of two successive storms close in time

b) Each storm was triggered not by a combination, but by independent mechanisms

c) The successive two Dst decreases had similar intensity, duration and shape of the Dst-curve.
**Complex Geomagnetic conditions on Sep 7-9 2017 event**

- **Solar flares- M-flare events:**
  - Two intense X-flares occurred on September 6\(^{th}\) (X2.2 at 08:57 UT and X9.3 at 11:52 UT).
  - A third intense flare X1.3 at 14:20 UT on September 7\(^{th}\) occurred some hours before the first Dst-minimum.
  - Another X8.2 was detected on September 10\(^{th}\).
  - During the considered storm event the sequence of M-flares accompanied the disturbances

- The first Dst minimum was caused by solar wind that was perturbed by the shock wave of the CME that occurred on Sep 6, but did not arrive to the Earth (not Earth directed).
- The shock wave of the next CME which was detected at Earth on Sep. 7 (22:38 UT) may have enhanced the fall of Dst to its first minimum. The CME material arrived at 11:00 UT Sep 8 at Earth causing the second Dst minimum. The first Dst minima caused by southward Bz-component of the IMF and by the consequent increases of the electric field induced into magnetosphere. Therefore, the ionosphere before the first Dst minimum was affected by flares.
- The ionosphere before and during the second Dst minimum development was affected by the previously and currently disturbed geomagnetic field and also with the preceding flares.
- **The two Dst minima were the results of two different reconnections between the Earth’s magnetic field and the interplanetary magnetic field triggered by different Solar events.**
We used RINEX files from GNSS permanent stations globally from:

a) International GNSS Service (IGS) [http://www.igs.org/]


These files have been processed with a calibration algorithm to obtain vertical total electron content, vTEC (Ciraolo, 2012)

This processing technique assumes ionospheric thin shell model (located at 350km of altitude) to obtain vTEC from slant total electron content (sTEC) at the Ionospheric Pierce Point (IPP)
Global ionospheric response to Sep 7-8, 2017 storm event

- Negative ionospheric response over middle & high-middle latitude areas except Asian sector.

- Positive ionospheric response over equatorial-low latitude areas in ALL 4 sectors. Not strong in India.

SSC=20:40 UT
In general positive ionospheric response over **equatorial-low latitude areas in ALL 4 sectors**

→ **Prölls classification: category 2:** Positive Storm Effects Caused by Changes in the Large-Scale Wind Circulation

- Large spatial and temporal extent. It may last a whole day and cover the whole range of middle latitudes
- These effects are most probably caused by changes in the large-scale wind circulation
- Poleward directed winds reduced and equatorial directed winds increased
- Frequently observed in the wake of travelling positive storm effects which initiate or accompany changes in the large-scale wind circulation
Negative ionospheric response over middle & high-middle latitude areas except Asian sector.

Prölls classification: category 4:
Negative Storm Effects Caused by Perturbations of the Neutral Gas Composition

**FIRST STORM EVENT**

**SECOND STORM EVENT**
Negative ionospheric response over **middle & high-middle latitude** areas except Asian sector

→ **Prölls classification: category 4:**
Negative Storm Effects Caused by Perturbations of the Neutral Gas Composition

- Negative storm most clearly observed in the morning sector
- It is marked by an anomalous low rate of ionization increase after sunrise
- Its duration is of the order of many hours and may reach days during continuous magnetic activity
- Sometimes it originates from changes in the neutral gas composition
- Its onset is determined by the preferential expansion of the composition disturbance in the midnight/early morning sector and by the effectiveness of competing processes
Ionospheric effects of Sep 7-8 2017

Spread F development over high mid-latitude ionosonde stations during the negative storm
Ionospheric effects of Sep 7-8 2017

Scintillation events over low- and mid-latitude stations during the negative storm

Data courtesy INGV
Ionospheric effects of Sep 7-8 2017 – Scintillation events in SH
Ionospheric effects of Sep 8 2017 – Scintillation events in SH

S4 – Sep 8, 2017
IONOSPHERIC RESPONSE

- Long-lasting, large enhancement of ionospheric TEC in a) all latitudes in Asian sector & in equatorial, low-latitudes in all sectors but slightly over India – consistent with PROLLS 2nd category

- Long-lasting, large depletion of ionospheric TEC in mid and high-mid latitudes in Europe, India and America sector – consistent with PROLLS 4th category

IONOSPHERIC EFFECTS

- Spread F development during negative storm

- Moderate/low scintillations effects in South Hemisphere regions (S. America & Australia)
Study of Joule Heating and Total Electron Content during Intense Storms of 2015-2017
Thermospheric O/N₂ Ratio from GUVI

- March 16, 2015
- March 17, 2015
- March 18, 2015
- March 19, 2015
LT = UT – 06.39h

Gjoa Haven 68.63°N 264.15°E

Differential VTEC
Satellite signal outages observed from a network of stations distributed over two hemispheres during periods of scintillations to check conformity with ICAO specified requirements for APV
The work is conducted preliminarily from Canadian High Arctic Ionospheric Network (CHAIN, Canada) network and CIGALA/CALIBRA (Brazil).

Specifically at Gjoa Haven and Presidente Prudente

Currently the same work is conducted from polar regions from stations operated by INGV.

Specifically at Longyearbean, Mario Zuccheli and Concordia
No cycle slip found from Canadian CHAIN stations on November 17, 2013.
Polar Stations chosen for measurement of cycle slips

1. Longyearbean LYB 78.2232° N, 15.6267° E geographic, Inclination 82.213 Declination 7.060 as per 21 September, 2012

2. Mario Zucchelli MZS 74.70° S, 164.11° E geographic, Inclination -82.576, Declination 134.636, as per 21 September, 2012

3. Concordia DMC 75.10°S, 123.35°E geographic, Inclination -80.723, Declination -141.236, as per 21 September, 2012

Only geomagnetic quiet days (Dst > -50 nT, kp <= 3 or Ap <= 15) are considered
Geographical Locations of the stations

- Longyearbyen
- Concordia
- Mario Zucchelli
Identify and characterize definitive condition for enhancement or inhibition of scintillation activities corresponding to intense geomagnetic storms for the low latitudes focusing on the geophysically sensitive Indian longitude sector
Siliguri and Calcutta data to look for EIA northern crest scintillations over India

Average position of the crest

Average position of the dip equator

Yao et al. Journal of Geodesy, 2017
September 2017 storm
Inhibition of scintillations

Post-sunset scintillations

Siliguri (26.72°N, 88.39°E)

05-Sep-2017 00:00 --> 11-Sep-2017 00:00
Post-sunset scintillations
FINAL AIM: CLIMATOLOGY OF IONOSPHERIC SCINTILLATIONS OVER INDIA

An example from the CIGALA/CALIBRA GNSS network in Brazil from 2013 to 2015
SERB, DST Sponsored ST Radar Project at the Ionosphere Field Station, Haringhata of the University of Calcutta

Principal Investigator: Prof. Ashik Paul
Co-Principal Investigator: Dr. J. Y. Siddiqui
Co-Investigator: Mr. Souvik Majumdar
**Stratosphere Troposphere Radar Facility at University of Calcutta Ionosphere Field Station, Haringhata**

The ST (Stratosphere Troposphere) Radar has proved to be a useful and versatile tool for lower atmospheric and ionospheric studies. Appreciating that the lower atmosphere is the seat of many interesting physical phenomena with implications to global change, University of Calcutta is implementing Eastern and North-Eastern India’s first ST Radar at 5.38 MHz at the Ionosphere Field Station, Haringhata located about 50 km northeast of the city.

**Objectives**

1. To study the dynamics of the tropopause and Stratosphere Troposphere Exchange (STE)
2. To study the convection process in troposphere
3. To study lower atmospheric turbulence
4. To study ionosphere E and F region irregularities

**Configuration**

ST Radar is fully active phased array radar, operating at 5.38 MHz. Its planar array consisting of 476 numbers of three-element Yagi antenna each fed by a dedicated 2-kW solid-state coherent Transmit-Receive (TR) Module. The array is configured in a near-circular shape spreading over an area of about 7000 m². An inter-element spacing of 0.7λ is adopted with an equilateral triangle grid to steer the beam up to a zenith angle of 30°. Antenna array is organized into 25 sub-arrays each consisting of 19 Yagi elements.

**Performance Parameters:**
- Height coverage: 0.5 - 20 km, with useful observations over at least 90% of time under all atmospheric conditions.
- Height resolution: 50 m up to 3 km altitude, 150 m from 3 to 20 km altitude
- Horizontal wind velocity: 1 - 70 m/s
- Vertical wind velocity: 0.1 - 30 m/s
- Velocity resolution: Better than 1% of maximum velocity value
- Wind accuracy: Horizontal wind speed 1 m/s, direction 10°
- Time resolution: 0.1-15 min for full profile
- Average power aperture product at the antenna feed point: 3 x 10^6 m² or better

**Deliverables:**
1. Three component wind measurements provide information about wave disturbances; 2. Spectral width measurements contain information on microscale turbulence; 3. The reflectivity measurements contain information on small scale gradients associated with tropopause; 4. The most important and unique capability of the ST radars is the measurement of the vertical wind component within a high degree of temporal and altitude resolution (typically ~30 sec and ~150 m). This unique capability gives the ST radars an enormous advantage over the conventional wind measurement techniques.

Funded by Science and Engineering Research Board (SERB), DST, GoI
- Fully Active Phased Array Radar, operating at 53 MHz with a bandwidth of 3MHz.
- Planar antenna array with 475 three-element Yagi antennas
- Beam Steering up to an off-zenith angle of 30°
- Organized into 25 sub-array groups each with 19 Yagi antenna elements and a shelter for housing TRMs

### Performance Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height coverage</td>
<td>0.5-20km for 90% of time</td>
</tr>
<tr>
<td>Height resolution</td>
<td>i) 50m up to 3km</td>
</tr>
<tr>
<td></td>
<td>ii) 150m from 3-20km</td>
</tr>
<tr>
<td>Horizontal wind velocity</td>
<td>1-70m/s</td>
</tr>
<tr>
<td>Vertical wind velocity</td>
<td>0.1-30m/s</td>
</tr>
<tr>
<td>Time resolution</td>
<td>5-15min for full profile</td>
</tr>
<tr>
<td>Average power aperture product</td>
<td>$3 \times 10^8$ Wm²</td>
</tr>
</tbody>
</table>

Original digital receiver design had 18 channels. But now it is being upgraded to 25 channels.
ST Radar Pilot Array (19-Element)
Control & Instrumentation Room
ST Radar Pilot Array, Ionosphere Field Station, Haringhata University of Calcutta (22.93 N, 88.50 E Geo)
ST Radar Pilot Subarray

- Pilot Array operational at Haringhata since April 2018
Tropical Cyclone Phailin
8 PM EDT Thu Oct 10 2013
Position 15° 8' N 88° 8' E
Maximum Winds 155 mph
Gusts 190 mph
Movement WNW at 6 mph

Satellite 5:27 AM UTC
1:27 AM EDT

Blue Marble base map imagery courtesy NASA
Near Real-Time RO Coverage

Prepared by UCAR/COSMIC
Scientific Uses of RO Data

• Ionosphere and Space Weather
  – Observe global electronic density distribution
  – Improve the analysis and prediction of space weather
  – Improve monitoring/prediction of scintillation (e.g. equatorial plasma bubbles, sporadic E clouds)
GNSS Receiver Network

• Motivation
  – Collection of navigation data message bits needed for radio occultation retrievals
  – Support GNSS precise orbit and clock determination
  – Support GNSS science research (free and open data policy)

• Deploying network of GNSS sites
  – ~15 sites
  – Multi-GNSS, triple frequency, geodetic quality

• Approach
  – Core network of UCAR maintained sites
    • We know hardware, firmware, data transmission paths and protocols
    • Aiming for redundant tracking globally to ensure robust coverage
  – Contributed sites
    • Data streams contributed by partner agencies, best effort basis
• 2019 additions
  – La Reunion
  – Kolkata
Multi-technique Characterization of Near-Earth Space Environment

ISSI Team led by Prof. Ashik Paul, Institute of Radio Physics and Electronics, University of Calcutta, Calcutta, India

THANK YOU