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Lecture 09: Ionosphere Observation with Radio Waves

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Source materials partially from Jade Morton and Robert Marshall
Outline

- Overview of ionosphere observation approaches
- GNSS network-based ionosphere observation and monitoring
- GNSS space-based ionosphere observations
 Ionosphere Irregularities: Temporal Evolution

Plumes or Plasma bubbles

- Electron Density
- Ion and Electron Temperature
- Ion Drift
- Ionospheric Composition

Jicamarca, Peru, vertical backscatter at 3m 3/21/1979


Fig. 2—Spectra for mixtures of O⁺, H⁺, and H⁺.

Gordon, 1964
World incoherent scatter radars
Ionosphere Irregularity: Vertical Structure

Ionosonde

HF typically 0.5–23 MHz or 1–40 MHz
Ionosphere Irregularity: 
Vertical Structure

Altair radar on Kwajalein island
0.96m wavelength

PLUMEX I rocket

Ionosphere Irregularity: Horizontal Structure

NASA's Ionospheric Connection Explorer (ICON)

- Understand drivers of ionospheric variability
- Explain how energy / momentum from lower atmosphere reach the space environment
- Explain how drivers create extreme conditions observed during solar-driven geomagnetic storms

Main instruments:
- **MIGHTI** is a Michelson Interferometer to measure winds and temperatures
- **FUV** is an FUV imager; observes UV emissions of N₂ and O to determine O/N₂ ratio
- **EUV** images 83.4 nm emission from O; resonantly scattered by O+: gives ion density
- **IVM** is the ion velocity meter; uses a Retarded Potential Analyzer (RPA) to measure relative velocity of ions, therefore winds, as well as temperature and density
GNSS Networks

IGS Global Ionosphere Map (GIM)

http://ionosphere.cn/
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Simplified Appleton-Hartree Equation

\[ f_g \approx 1 \text{MHz} \quad f_p \leq 10 \text{MHz} \]

At GPS frequency, \( f \sim \text{GHz} \):

\[
X = \left( \frac{f_p}{f} \right)^2 \ll 1 \quad Y = \frac{f_g}{f} \ll 1
\]

\[
n_\phi = 1 - \frac{X}{1 - \frac{Y^2 \sin^2 \theta_B}{2(1 - X)} \pm \sqrt{\frac{Y^4 \sin^4 \theta_B}{4(1 - X)^2} + Y^2 \cos^2 \theta_B}}
\]

\[
n_\phi \approx 1 - \frac{X}{2} \pm XY |\cos \theta_B| - \frac{1}{4} X \left( \frac{X}{2} + Y^2 (1 + \cos^2 \theta_B) \right)
\]

Vacuum 1\(^{\text{st}}\) order 2\(^{\text{nd}}\) order 3\(^{\text{rd}}\) order

\[
n \quad 1 \quad \frac{X}{2} \quad 1 \quad \frac{e^2}{2m_0 f^2} N_e = 1 \quad 40.3 \frac{N_e}{f^2}
\]
Ionosphere Disturbance Impact on Mid-latitudes

Challenges in Measuring Ionospheric Irregularities

1. Availability

   Receivers cease to function if GNSS signal traverse irregularities
   → Data are not available when needed most!

2. Accuracy

   \[(\text{iono} + \text{other}) \times h(t) = \text{Observed Effects}\]
   
   Ionosphere effects ≠ Observed Effects
Availability Issue: March 17-18, 2015 St. Patrick’s Day storm

Accuracy: Scintillation Indices

**Phase scintillation index:** \( \sigma_\phi = std \left( detrend(\phi_{s,k}) \right) \)

**Amplitude scintillation index:** \( S_4 = \sqrt{\frac{\langle SI^2 \rangle - \langle SI \rangle^2}{\langle SI \rangle^2}} \)

**Signal intensity (power):** \( SI = \frac{SI_{raw}}{SI_{trend}} \)

\( SI_{raw} = NBP - WBP \)

**Narrowband power:** \( NBP = \left( \sum_{i=1}^{M} I_i \right)^2 + \left( \sum_{i=1}^{M} Q_i \right)^2 \)

M: number of correlation blocks over a selected period
Typical setting: \( T_I = 1 \text{ms} \rightarrow M = 20; \ T_I = 10 \text{ms} \rightarrow M = 2 \)

**Wideband power:** \( WBP = \sum_{i=1}^{M} I_i^2 + \sum_{i=1}^{M} Q_i^2 \)

**Rate of TEC Index (ROTI):** \( ROTI = \sqrt{E \left[ \frac{|TEC(t + \delta t) - TEC(t)|^2}{\delta t^2} \right]} \)
Global SDR Data Collection Network

>2 PB data and growing
- Dedicated data center and processing facility
- Machine learning, data science

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Low Latitude Scintillation Example

Peru
3/11/2013
13:30UTC
Plasma Velocity Estimation

Ionosphere TEC and Disturbance Forecasting

Machine Learning Forecast Framework Using ConvLSTM:
(Convolutional Long Short-Term Memory)

(Shi et al., 2015)

Input/Output

<table>
<thead>
<tr>
<th>Input/Output</th>
<th>TEC Map: Background Ionosphere</th>
</tr>
</thead>
<tbody>
<tr>
<td>ROTI Map: Ionosphere Disturbances</td>
<td></td>
</tr>
</tbody>
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Ionosphere Disturbance Forecasting with Ground GNSS Networks

- **GNSS Receivers**
- **IPP**
- **Raw ROTI**
- **Interpreted ROTI**

- Lead time steps: 10 minutes
- Resolution: 1° Latitude by 1° Longitude
- Select data of storm days with SYM-H index < -40 nT
Ionosphere Disturbance Forecasting Results:

Ionosphere Disturbance Forecast Results:

(Liu et al., 2021)
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Filling the Data Gap: LEO Satellite-Based Observations

GNSS Radio Occultation (GNSS-RO)

Progression of Tangent Point for a Setting (desending) Occultation

Tangent point

V_{GPS}  

V_{LEO}

cosmic.ucar.edu

GNSS Reflectometry (GNSS-R)

BDS  

GLONASS  

QZSS

Calm Ocean  

Moist Surface  

Sea Ice

GPS  

Galileo

LEO

LEO

LEO

LEO

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Yue, X., Wan, W., Liu, L., Liu, J., Zhang, S., Schreiner, W. S., ...
& Hu, L. (2016). Mapping the conjugate and corotating storm-enhanced
density during 17 March 2013 storm through data assimilation.
GNSS RO Ionosphere Retrieval

Non-Occulting Reference
GPS Satellite

Non-Occulting POD
GPS Satellite

0.1 Hz
L1 & L2

LEO Satellite
MicroLab - 1

1 Hz
L1 & L2

1 Hz LC

Occulting GPS Satellite

1 Hz
L1 & L2

1 Hz LC

Orbit Altitudes
LEO Satellite = 735 km
GPS Satellite = 20,231 km

GNSS-RO TEC Retrieval

\[
T_E C \approx \frac{1}{\beta} \Delta \phi_{12} + \Delta B_{12}
\]

\[
\frac{1}{\beta} = \frac{1}{40.3} \frac{f_2^2 - f_1^2}{f_1^2 f_2^2}
\]

How to calibrate/estimate bias?

- GNSS satellite bias: use ground receiver network estimations, IGS products
- LEO satellite receiver bias:
  - Find geometries that tend to result in minimum TEC along a raypath and use climatological models of ionosphere to estimate the small Ne and TEC in the region. Example: at high latitudes where the ray path traverses regions of open magnetic fields near the poles.
  - Set TEC to 0 along minimum TEC ray path
  - Rely on receiver built-in calibration mechanism
Ionosphere Ne Profile Retrieval

Assumptions: Straight ray path and spherical symmetry
(Ne varies only with radius or altitude, not horizontally along the ray path)

\[ TEC = \int_{\text{raypath}} Ne(s)ds \]

\[ s(r) = \sqrt{r_0^2 - r_t^2} - \sqrt{r^2 - r_t^2} \]

\[ \frac{ds(r)}{dr} = \frac{r}{\sqrt{r^2 - r_t^2}} \]

\[ TEC(r) = 2 \int_{r_0}^{r_t} \frac{rNe(r)}{\sqrt{r^2 - r_t^2}} dr \]

\[ Ne(r) = \frac{1}{\pi} \int_{r}^{r_0} \frac{dTEC}{dr_t} \frac{1}{\sqrt{r_t^2 - r^2}} dr_t \]

Mannucci et al., Chapter 31 GNSS Radio Occultation, PNT21, 2020
Ionospheric Observations from GNSS-RO

Ne profiles, TEC, Scintillation

GNSS-R Phase-Delay Altimetry

Arctic and Antarctic: High Rate Coherent Reflections

42% over sea ice. 75% over 1st year ice

Example TEC Retrieval from Spire Data: Kara Sea

Ionosphere Structure Observation GNSS-R

(a) 2022-08-17T03-11-54
(b) VTAC (TECU)
(c) 2022-08-17T17-46-17
(d) VTAC (TECU)

SP

IP1

IP2

TEC

GNSS-R

IP1 - Madrigal

GNSS-R

IP2 - Madrigal

Time (s)

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GNSS-R Monitoring Ionospheric Disturbances