Earth’s Ionosphere
Groundbased Measurements
and Real-time Ionospheric Modeling

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Acknowledgement

The Lowell Team
UML - LDI
Outline

• Ionosonde observations of the ionosphere
• International Reference Ionosphere -- IRI
• IRI-based Real Time Assimilating Mapping-- IRTAM
• Bottomside Traveling Ionospheric Disturbances -- TIDs
Earth’s Ionosphere & Space Weather
Solar Wind-Magnetosphere Interaction
Ionospheric Effects on Radio Applications

- Sun
  - Extreme Ultraviolet Radiations
    - Form the ionosphere
  - Solar X-rays
    - Penetrate into the D-region
- Visible Lights
  - Reaching the ground
- Broadcasting/Communication/Observation Satellites
- Navigation Satellites (GPS)
- Ionosphere
  - F-region
  - E-region
  - D-region
- Radio Absorption
- Ionospheric Storm
- Interference
- Scintillation
- Propagation Delay
- HF Communications/Broadcasts
- TVIFM Radios
- Satellite Operation
- Land Survey/Navigation

NICT

Boston College Seminar Series • Dec 1, 2016
Electron Density Distribution
Ionosphere and Plasmasphere

IRI EDP and Parameters

Topside
hmF2
hmF1
F2
B0, B1
F1
D1
hmE
NmE
NmF1
NmF2

Plasmasphere EDP

Geocentric Distance (Re)
Electron Density (cm⁻³)

log N
Measuring the Bottomside Electron Density Profile

At the reflection point:

O-wave is perp to $B_g$, and $f_N = f$

X-wave is parallel to $B_g$ (not shown here)
Digisonde Ionogram → Autoscaling → real-time Electron Density Profile

Digisonde: Reinisch et al., 2009
NHPC profile: Reinisch und Huang, 1983
ARTIST: Galkin et al., 2009
Comparing Digisonde NHPC profiles with incoherent scatter radar measurements

Several thousand inverted profiles from Digisonde ionograms at Millstone Hill and Arecibo were compared with the profiles derived from co-located incoherent scatter radar measurements for half a solar cycle from 1990-1996 [Chen, et al., 1993].

Comparison summary:
1. The height differences in the F layer are in the average less than 5 km
2. The valley model is very good in general, but during twilight or ionosphere storms larger deviations occur.
Complicated ionogram signatures in the presence of Medium- and Large-Scale TIDs

ARTIST ionogram scaler is capable of extracting vertical echo traces and calculate the vertical EDP.
Ionogram during disturbed conditions

Eglin, FL

22:15 LT
Phase and Group Velocities in a Magnetoplasma

In a dispersive medium, the phase and group velocities differ. The phase velocity is (neglecting collisions)

\[ v_{ph} = \frac{c}{\mu} \]. Since \( \mu < 1 \) in a plasma, \( v_{ph} > c \)

The group velocity in a dispersive medium is

\[ v_g = \frac{d\omega}{dk} \]

The group refractive index is

\[ \mu' = \frac{c}{v_g} = c \frac{dk}{d\omega} = \frac{d}{d\omega} (\mu \omega) = \mu + \omega \frac{d\mu}{d\omega} \]

Neglecting the magnetic field and collisions (\( Y=0 \) and \( Z=0 \)), \( \mu = \sqrt{1 - (f_N/f)^2} \). Then

\[ \mu' = \frac{d}{df} (\mu f) = \frac{1}{\mu} \quad \text{or} \quad \mu \mu' = 1 \]

Therefore \( v_g < c \)

Note that \( v_g \rightarrow 0 \) at the reflection point where \( \mu = 0 \).

Important:
Directions of \( v_{ph} \) and \( v_g \) are different when using the plane wave description (as is usually done)!

Huang and Reinisch [2012] showed that using spherical wave solutions makes \( v_{ph} \parallel v_g \).

The indices of refraction $n_\pm$ are given by the **Appleton-Lassen** formula:

$$n_\pm^2 = 1 - \frac{X}{1 - iZ - \frac{Y_T^2}{2(1 - X - iZ)} \pm \sqrt{\frac{Y_T^4}{4(1 - X - iZ)^2} + Y_L^2}}$$

with

$$k = \frac{\omega}{v} = \frac{\omega n}{c}$$

$$X = f_N^2/f^2; \quad Y = f_B/f; \quad Z = v/2\pi f$$

where

$$f_N^2 = \frac{e^2}{4\pi \varepsilon_0 m} N \cong 80.6 \, N \quad (N \text{ in } m^{-3}, \quad f_N \text{ in } Hz)$$

$$f_B = \frac{eB}{2\pi m} \cong 1.4 \, MHz$$

*often called “Appleton-Hartree” formula, but Hartree (1931) had included an incorrect dielectric polarization term. Lassen had derived the correct $n_\pm$ in 1927.*
Digisonde Ionogram → Autoscaling → real-time Electron Density Profile

Digisonde: Reinisch et al., 2009
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Off-vertical Echo Traces and Severe Spread F

Autoscaled data

- Oblique echoes: from East
- from South-South-East
- X-data
- Vertical O-trace
- Conventional ionogram

Station YYY Day DDB HHMM F1 FF5 S AXN PPS IGA FS
Tronsa 2002 Apr 07 0917 1916 HH0 000-1 715 200 -0+ B2

- MUF: 16.64
- N: 2794
- D: 3000
- h'F: 255
- h'F2: N/A
- h'E: 110
- h'Es: 125
- zmF2: 326
- zmF1: N/A
- zmE: 195
- vF2: 111
- vF1: N/A
- vE: 15
- B0: 112.0
- B1: 2.26

D 100 200 400 600 800 1000 1500 3000 [km]
MUF 6.7 6.8 7.0 7.4 7.9 8.7 11.0 16.6 [MHz]
Groundbased Ionosondes -- Digisonde Data Products

- 1931: First ionogram
- 1936: 5 ionosondes in the world
- 1957: 150 ionosondes in the world
- 1969: First Lowell Digisonde built
- 2016: <a few hundred?> ionosondes ever built
  - 231 ionosonde locations registered in SPIDR (1942... current)
  - 164 Lowell Digisondes (1969 .... current)
Digisonde History

Digisonde 128 (1969)
Digisonde 256 (1978)
DPS4 (1993)
DPS4D (2006)
Global Ionosphere Radio Observatory (GIRO)

[Reinisch and Galkin, 2011]
24-hour GIRO ionogram movies

http://giro.uml.edu/IonogramMovies/

Boulder  C.Paulista  Dourbes  El Arenosillo  Ebro  Eglin AFB

Gakona  Hermanus  Irkutsk  Jicamarca  Jeju Is.  Kwajalein Is.

Millstone Hill  Moscow  Norlisk  Pt. Arguello  Pruhonice  RRL-Chilton
Ionospheric plasma density specifications in real time

Plasma Frequency

\[ f_p [kHz] \approx c_p N_e^{0.5} [el/m^3] \]

\[ c_p = 0.898 \times 10^{-5} \]


http://ionosphere.meteo.be
HAARP Heating Experiments

Ionograms show the bottomside of expanding plasma ball appearing as an artificial ionization layer.

Credits: Todd Pedersen and HAARP/AFRL team
HAARP Heating Campaign 2008
Digisonde Skymap and Waterfall Display

Topside of the expanding plasma structure ~50 km wide, accelerating upward along the magnetic field line at 80-100 m/s
EDP from Ionospheric Radio Occultation

Comparison with ISR

\[ TEC_f = \sum_{i=1}^{N_{\text{vox}}} n_{eij} \cdot ds_{ij} \]

[Jakowski et al., 2007]
COSMIC and Digisonde concurrent measurements

Profiles obtained by COSMIC and DPS4D Digisonde

Corresponding Ionogram

[From Baiqi Ning, 2014]
IRI-based Real Time Assimilative Mapping -- IRTAM
The new IRTAM-2016

- Digisonde GIRO network sends measured ionogram data in real time to LGDC for assimilation into the IRI maps for fof2, hmF2, B0, B1

[Galkin et al., 2012]
IRI and IRTAM-2016

IRI and IRTAM-2016 assimilates the measured foF2, hmF2, B0, and B1 values

**Anchor points:** all measured by GIRO Digisondes

- NmF2, hmF2
- NmF1, hmF1
- NmE, hmE
- B0, B1, D1

**Time expansion in IRI**

\[
foF2(t; \lambda_G, \varphi_G; \lambda_M, \varphi_M) = a_0(\lambda_G, \varphi_G; \lambda_M, \varphi_M) + b_0(\lambda_G, \varphi_G; \lambda_M, \varphi_M)t \\
+ \sum_{i=1}^{6} \left[ a_i(\lambda_G, \varphi_G; \lambda_M, \varphi_M)\cos\Omega_it + b_i(\lambda_G, \varphi_G; \lambda_M, \varphi_M)\sin\Omega_it \right]
\]

Similarly for hmF2, B0 and B1

IR TAM uses same expansion to represent the measured data between t-24h and t, and finds new coefficients \(a_i', b_i'\).
Real-Time IRI
3D global bottomside ionosphere in real-time

15 minute cadence

Diurnal fit to GIRO data
4D data assimilation:
24-hour fit of minimizing differences between IRI and GIRO

Port Stanley data courtesy of Sarah James, RAL UK

Global Spatial fit
Jones-Gallet Gk basis (76), CCIR
= total map coefficients: 1064
[24-hour global weather]

NmF2, hmF2, B0, B1 anchors

x 52 GIRO stations
In Combination with VTEC:

Deviation from expected quiet-time behavior
Red: larger than model     Blue: smaller than model
Real-Time IRI Improvement over Climatology
Average improvement ~ factor of 2 in terms of $\langle$Obs-Model$\rangle$ error reduction (15 million comparisons)

foF2 Improvement factor
Comparisons with control site included vs excluded

<table>
<thead>
<tr>
<th>Cntl Site</th>
<th>Included vs excluded</th>
<th>Lost Q</th>
</tr>
</thead>
<tbody>
<tr>
<td>BC840</td>
<td>2.20 vs 1.75</td>
<td>20 %</td>
</tr>
<tr>
<td>IF843</td>
<td>1.92 vs 1.39</td>
<td>28 %</td>
</tr>
<tr>
<td>WP937</td>
<td>2.14 vs 1.46</td>
<td>32 %</td>
</tr>
<tr>
<td>AU930</td>
<td>2.10 vs 1.34</td>
<td>36 %</td>
</tr>
<tr>
<td>EG931</td>
<td>2.00 vs 1.28</td>
<td>36 %</td>
</tr>
</tbody>
</table>

IRTAM foF2 = typical x2 improvement

Green sites: loss of quality < 40%

Test Period: 2013.02.19 to 2013.06.11
Not all GIRO sites are equally important

Test Period: 2013.02.19 to 2013.06.11

**foF2 improvement factor**
Comparisons with control site included vs excluded

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<tr>
<th>Cntl Site</th>
<th>Included vs excluded</th>
<th>Lost Q</th>
</tr>
</thead>
<tbody>
<tr>
<td>MHJ45</td>
<td>2.11 vs 1.24</td>
<td>41 %</td>
</tr>
<tr>
<td>PA836</td>
<td>2.61 vs 1.29</td>
<td>51 %</td>
</tr>
<tr>
<td>PRJ18</td>
<td>2.86 vs 1.05</td>
<td>63 %</td>
</tr>
</tbody>
</table>

No improvement to IRI climatology when PRJ18 is excluded

Red sites: loss of quality > 40%
Testing
IRTAM-2016 Performance
foF2 prediction for Austin

Neighboring GIRO sites adequately steer the foF2 prediction for Austin
Digisonde Tilt and TID Measurements

- Vertical incidence and oblique sounding
- Electron Density Profiles
- Ionospheric Tilt
- D2D TID Measurements
Digisonde Tilt Measurements

- Overhead skymap shows locations of echo sources:
  - $p_i$, the virtual range (1/2 ToF·c)
  - $\theta_i$, the zenith angle, and
  - $\phi_i$, the azimuth angle (counted from the north to the east).

- Vector to “cluster” center specifies tilt:
  $\theta_0$ is the zenith angle of the normal to the isodensity contour, and $\phi_0$ the azimuth angle of the normal.

[Huang and Reinisch, 2006]
TID Measurements

FREQUENCY-ANGLE-SOUNDING (FAS) TECHNIQUE

OUTPUT: Period, Phase, Amplitude, and velocity vector of TID

[Paznukhov et al., ASR, 2012]
Net-TIDE Europe

https://sites.google.com/site/spsionosphere/

The DPS4D network in Europe
First phase of TID Experiments

A splinter meeting on the Net-TIDE project will be held in the 13th European Space Weather Week, on Friday 18 November 2016 from 3 to 4.30pm.

Click on the flyer for more information.
Digisonde-to-Digisonde (D2D) sounding detects TIDs
(measurements from the NetTIDE Project were used)\(^1\)

\(^1\)Technique developed under AFRL SBIR project RETID, 2016
Simulating Raytracing and Mirror Reflection for TID

We assume that during the passage of a TID the electron density \( N(\lambda, \varphi, h, t) \) at height \( h \), time \( t \), and location \((\lambda, \varphi)\) can be represented by

\[
N(\lambda, \varphi, h, t) = N_{\text{IRTAM}}(\lambda, \varphi, h, t)\left[1 + A \cos(\Omega t - KD + \Psi_0)\right]
\]

The phase distance \( D \) depends on the azimuth of the direction of the TID propagation. The angular frequency \( \Omega \) of the TID wave is related to its period \( T \), and the wave number \( K \) to the wavelength \( \Lambda \):

\[
\Omega = \frac{2\pi}{T}, \quad K = \frac{2\pi}{\Lambda}.
\]
TID Detection and Evaluation

- $f_p = f$
- $A_c$
- $\Phi_0$
- $V_p$, $\Theta$
- $\Omega_m$
- $\epsilon$, $\beta$
- $\rho_1$, $\rho_2$
- $f_D$
D2D Signal and TIDs: Modeling

- Dist = 324 km; 8 MHz

- Dist = 601 km; 5 MHz

- Dist = 601 km; 5 MHz

Oct 15, 2013; foF2 = 5.5 MHz
TID (model2, A=2.7%, az=180, λ=300 km, T=20 min)

Oct 15, 2013; foF2 = 11 MHz
TID (model2, A=13.8%, az=180, λ=200, T=30 min)
D2D Signal and TIDs: First results

D2D sounding: Dourbes-to-Roquetes

FAS Computations

<table>
<thead>
<tr>
<th>Time</th>
<th>Amplitude, %</th>
<th>Wave length, km</th>
<th>Azimuth, °</th>
<th>Period, min</th>
<th>Velocity, m/s</th>
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</thead>
<tbody>
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<td>810</td>
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<td>80</td>
<td>169</td>
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<td>80</td>
<td>178</td>
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<td>168</td>
<td>80</td>
<td>199</td>
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<td>167</td>
<td>80</td>
<td>236</td>
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<td>1253</td>
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<td>80</td>
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<td>299</td>
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<td>188</td>
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<td>361</td>
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<td>1684</td>
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<td>80</td>
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<td>300</td>
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<td>208</td>
<td>80</td>
<td>332</td>
</tr>
</tbody>
</table>

Large-scale TID propagating southward [from auroral region]
References


