The Ionosphere and its Impact on Communications and Navigation

Tim Fuller-Rowell
NOAA Space Environment Center and
CIRES, University of Colorado
Customers for Ionospheric Information

• **High Frequency (HF) Communication (3-30MHz)**
  – ground-to-ground or air-to-ground communication
  – establish accurate maximum useable frequencies
  – support automatic link establishment systems
    • e.g., civilian aviation, maritime, frequency managers

• **Single Frequency GPS Positioning and Navigation**
  – single frequency potential sub-meter accuracy positioning
    • e.g., civil aviation, advanced vehicle tracking, potential for E911 improvements

• **Dual Frequency GPS Positioning and Navigation**
  – decimeter accuracy 10-50 cm
    • e.g., real-time kinematic (RTK), autonomous transportation, off-shore drilling and exploration
  – rapid centimeter accuracy positioning 1-2 cm
    • e.g., surveyors, possible InSAR (land radar) applications
Customers for Ionospheric Information

• Satellite Communication
  – specification and forecast of scintillation activity
    • e.g., satellite operators, drilling companies

• Situational Awareness
  – Depressed maximum useable frequencies
  – Steep horizontal gradients
  – Unusual propagation paths
  – Larger positioning errors
  – High probability of loss of radio signals
The Thermosphere and Ionosphere
Electron Density Profile

Vertical profile of electron density from GPS/MET compared with Millstone Hill incoherent scatter radar observations

Courtesy: Chris Rocken NCAR
Solar Flares

Increased X-ray flux
D-region ionization

Arrival time: 8 minutes
Duration: 1-2 hours

Effects:
• HF absorption
• Disruption of low frequency navigation
• GPS navigation

Users: mariners, coast guard, HF frequency managers, commercial aviation, military
Solar Proton Events

High energy particles

Arrival time: 15 mins to few hours
Duration: several days

Effects:
• Single event upsets (SEU)
• Deep dielectric charging
• **HF absorption**
• **Low frequency navigation outage**
• Radiation hazard

Users: satellite operators, HF frequency managers, commercial aviation, mariners, astronauts, …..
Coronal Mass Ejections

Geomagnetic Storm

Arrival time: 1-3 days
Duration: 1-2 days

Effects:
- Spacecraft charging
- Satellite drag
- HF Communications
- GPS Navigation
- Induced currents

Users: Power companies, satellite operators, HF frequency managers, FAA, military, GPS,...
Effect of Solar X-rays on D-Region and HF Propagation.

- D-Region Absorption Product based on GOES X-Ray Flux (SEC Product)
  - The map shows regions affected by the increased D-region ionization resulting from enhanced x-ray flux during magnitude X-1 Flare

Dayside response
Zenith angle dependence
Time scale follows source
Solar Flares: HF Absorption Radio Blackout
Radio Wave Propagation
Fort Collins, CO to Cedar Rapids, ID

Signal Strength at 10 MHz

[Graph showing signal strength over time with distinct sections for night and day]
Radio Wave Propagation
Fort Collins, CO to Cedar Rapids, ID

Signal Strength at 10 MHz

Flare
TEC GPS Differential Phase measurements

NKLG Differenced vtec 2003-10-28 - 2003-10-27

Equatorial African station, near noon

X17
Solar Protons

GOES8 Proton Flux (5 minute data)

Updated 2002 Apr 25 23:56:06 UTC
NOAA/SEC Boulder, CO USA

Solar Protons Detected by PDES
14 passes, Last at 2000 07 15 10:34 UTC, from NOAA-15

NOAA/Space Environment Center
PCA depends on solar illumination

$O_2 - e^-$ attachment process in the D-region
Combined X-ray and PCA
Coronal Mass Ejection

A single eruption can release a billion tons of material into the solar wind. Speeds can exceed several million miles per hour. Energetic particles accelerated by shocks cause bright flashes in the image (and in DNA!)
Increased energy input to the upper atmosphere: auroral particle precipitation and magnetospheric convection electric field

\[ E_{pc} \text{ 10 - 300 kV in minutes} \]
Large temperature and circulation changes in the upper atmosphere
Oxygen Depletions Imaged from Space

81 295 17:45:38

wipe out ionosphere

Strong correlation between O/N₂ and ionospheric depletions
STORM Time Empirical Ionospheric Model

F region critical frequency (f\(\text{cF2}\)) scaling factor

This value represents the adjustment needed to the climatological mean due to geomagnetic activity.

Corrected \(f\text{cF2} = \text{"scaling factor"} \times f\text{cF2(mean)}\)

Geomagnetic activity has been active, therefore substantial ionospheric adjustments are necessary in some sectors.

Legend and Color Scale
- black line = 1.0 \(\rightarrow f\text{cF2 monthly mean.}\)
- blue line \(\rightarrow\) deviation up to 10% from the monthly mean (minor of no adjustments required.)
- green symbol \(\rightarrow\) deviation between 10% and 25% from the monthly mean (significant adjustments required.)
- yellow symbol \(\rightarrow\) deviation of more than 25% from the monthly mean (substantial adjustments required.)

Integral of \(ap\) (latest value) = 1363.85

Latest values at DOY = 198 UT = 23

Updated Jul15 2000, 23:29:06 UT

NOAA/SEC Boulder, CO USA
The geomagnetic storm on Monday August 18th 2003 wiped out the normal daytime peak in TEC and electron density over North America.

Normal quiet-day maximum on August 17th

Ionospheric depletion on the 18th during the storm
Electrodynamics

- Penetration and dynamo electric fields can strengthen the EIA and deepen equatorial holes.

- Ring current polarization electric fields can transport ionospheric plasma and produce troughs.

- Huge gradients in plasma density ensue.
CHAMP (400 km) OSEC: Halloween
Mannucci et al. 2005
One of the challenges:

October 29th, 2003 stationary “walls” of TEC compromise integrity of LAAS

TEC “walls”:
130 TEC units over 50 km
20 m of GPS delay;
walls move 100 to 500 m/s

Courtesy: Tom Dehel, FAA
Steep TEC gradients increase GPS positioning errors.

High correlation between disruption of WAAS availability and TEC gradients.
The Kalman Filter and extracting “information”
Primary Product: Vertical TEC

Real-time ionospheric maps of total electron content every 15 minutes
Slant-Path TEC Maps

2-D maps of of slant path TEC over the CONUS for each GPS satellite in view updated every 15 minutes

Applications:
1. Ionospheric correction for single frequency GPS and NDGPS positioning
2. Dual-frequency integer ambiguity resolution for rapid centimeter accuracy positioning
Scintillations and Maps

Distribution of high scintillation events

Signal-to-noise ratio

Courtesy:
Paul Straus
Aerospace Corporation
Electron Density $[\log/m^3]$
Scintillations

Ionosphere

Heavy Fluid

Light Fluid

Steep bottomside density gradient during / after sunset

Fluid instability analog (Rayleigh-Taylor instability)
Plasma Bubbles

WBMOD: empirical model

physical modeling
GUVI Nighttime FUV Ionosphere Observations

\[ e + O^+ \rightarrow O^* (135 \text{ nm}) \quad \Rightarrow \quad I = \alpha \int n_e^2 \, ds \]
Motivation: Planetary wave periodicities in dayside ionosphere

Dayside electrodynamics during 2001

Electrodynamics drives plasma transport

Possible PW signatures

Normalized PSD

Courtesy D. Anderson & A. Anghel (2006)
Mid-latitude day-to-day variability in ionospheric total electron content

Lat. 30°N  Lon. 100°W

TEC (TECU)

DOY (May 01-31, 2004)

Day of the Year 2004

0  50  100  150  200  250  300  350

0  0.5  1  1.5  2  2.5  3

Period [days]

Kp

Current
10-day average
Kp
El Niño

GW

PW

Tides

QBO

SAO

Electrodynamics

Scintillations

Ionospheric Bubbles

 Courtesy of Rashid Akmaev
Tidal signatures in nightside Equatorial Ionospheric Anomaly

IMAGE composite of 135.6-nm O airglow (350-400 km) for March-April 2002 and magnitude of tidal temperature oscillations at 115 km (Immel et al., 2006).
## Conclusion

- Many of the space weather effects on communication and navigation are a consequence of the response of the upper atmosphere to solar flares, coronal mass ejections, and solar proton events.

- Day-to-day variability can also arise from the connections between terrestrial and space weather.