Ionospheric Measurement
Bottom Side Ionospheric Sounding

Presentation to Brown University

Mathematical and Computational Challenges in Radar and Seismic Reconstruction
11 Sept 2017

Dr. Frank C. Robey, Dr. Gregory P. Ginet

This material is based upon work supported by the Department of the Navy under Air Force Contract No. FA8702-15-D-0001. Any opinions, findings, conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the Department of the Navy.
Outline

• Introduction to the ionosphere

• Ionospheric impacts on RF signals

• Areas for research

• Conclusion
The Space Environment

- Photons (X-rays, EUV, radio flares)
- Solar wind
- Interplanetary magnetic field (IMF)
- Solar Energetic Particles (SEP)
- Coronal Mass Ejections (CME)
- Galactic Cosmic Rays (GCR)
- Earth’s magnetic field
- Ionosphere
- Van Allen Belts
- Aurora
Space Environment

Solar Activity
- Electromagnetic Waves (e.g. solar flares)
  - Travel time: Minutes
- Energetic Particles (e.g. solar particle events)
  - Travel time: hours
- Solar wind plasma & B field (e.g. Coronal mass ejections)
  - Travel time: days

Near-Earth Consequence
- Magnetosphere
  - Plasma environment
  - Radiation belts
- Ionosphere
  - Aurora
  - Electron density variations
  - Radio wave absorption
  - Enhanced ionization
- Thermosphere
  - Particle heating
  - UV heating
- Earth Surface
  - Ground induced currents

System Impact
- Spacecraft Ops
  - Electronics degradation
  - Sensor performance limits
  - Hostile action masking
- SIGINT
  - Geolocation errors
  - Signal disruption
- Communications
  - Signal disruption
  - HF signal frequency and range limits
- Missile Warning & Tracking
  - False targets
  - Range/elevation accuracy
- Power Distribution
  - Transformer breakdown

Solar Activity
- Electromagnetic Waves (e.g. solar flares)
- Energetic Particles (e.g. solar particle events)
- Solar wind plasma & B field (e.g. Coronal mass ejections)

Near-Earth Consequence
- Magnetosphere
  - Plasma environment
  - Radiation belts
- Ionosphere
  - Aurora
  - Electron density variations
  - Radio wave absorption
  - Enhanced ionization
- Thermosphere
  - Particle heating
  - UV heating
- Earth Surface
  - Ground induced currents

System Impact
- Spacecraft Ops
  - Electronics degradation
  - Sensor performance limits
  - Hostile action masking
- SIGINT
  - Geolocation errors
  - Signal disruption
- Communications
  - Signal disruption
  - HF signal frequency and range limits
- Missile Warning & Tracking
  - False targets
  - Range/elevation accuracy
- Power Distribution
  - Transformer breakdown
The ionosphere is a series of ionized gas (plasma) layers created by solar X-ray/EUV/UV radiation. Plasma density varies by location, time of day, season and solar & geomagnetic activity. Dynamics are driven by heliosphere and tropospheric processes.
Atmospheric Regions

Ionospheric Dynamics

High latitude region
- Magnetosphere is strong driver

Equatorial “Appleton” anomaly
- Neutral winds are strong driver

Complex space weather system is challenging to measure and model

AFRL, https://directory.eoportal.org/web/eoportal/satellite-missions/content/-/article/cnofs
Ionosphere Variability Due to Solar Activity

- Vertical sounder backscatter measurements illustrate the variability of the ionosphere over daily and annual cycles.

Sunspot measurements from nasa.gov. Millstone sounder from www.giro.com
Tohoku-Oki Earthquake and Tsunami Observed in Earth's Upper Atmosphere

- There is clear coupling between geological events and the ionosphere
- A clear example is provided by imaging using vertical total electron content (VTEC) measurement as the source
- VTEC is easily measured by GPS
- Waves in the ionosphere align with the resulting tidal wave

March 11, 2011

https://photojournal.jpl.nasa.gov/catalog/PIA14430
Outline

• Introduction to the ionosphere

• Ionospheric impacts on RF signals

• Areas for research

• Conclusion
Ionospheric Effects on RF Systems

Index of refraction

\[ \eta = \sqrt{1 - \frac{f_{p}^{2}}{f^{2} + f_{p} \cdot f_{c} \cos \theta}} \]

- \( f_{p} [\text{Hz}] \approx 9 \cdot 10^{6} \sqrt{n_{e} [\text{cm}^{-3}]} \)
- \( f_{c} [\text{Hz}] \approx 2.8 \cdot 10^{6} B [\text{Gauss}] \)
- \( \theta = \text{angle between } B \text{ and } k \)

Dispersive (plasma density effect)

Mode splitting (magnetic field effect)

Diurnal variations
Scale \( \geq 1000 \text{km} \)

Traveling ionospheric disturbances
(scale \( >10 \text{ km} \))

Small scale irregularities
(<100 m)

Reflection

VLF-HF communications
Over-the-horizon radar

Refraction

UHF & VHF communications
UHF radar tracking

Scintillation

GPS
Ionospheric Characterization

- Extrapolate, interpolate, & propagate measurements to characterize varying ionosphere where there are no measurement sources
- Follow the ionospheric dynamics

From: F. Robey, HFGeo Proposer’s day presentation: https://www.iarpa.gov/index.php/research-programs/hfgeo/phase-1b-baa
Ionospheric Measurement

- Vertical and oblique ionosonde are the reference standards for bottom-side ionospheric understanding
- There are insufficient numbers and density
- Known reference points at fixed frequencies provide excellent information on ionospheric motion

From: F. Robey, HFGeo Proposer’s day presentation: https://www.iarpa.gov/index.php/research-programs/hfgeo/phase-1b-baa
• The refractive index for magnetized plasma is given by the Appleton-Hartree equation (e.g., Sen and Wyller 1960):

\[
n^2 = 1 - \frac{X}{1 - iZ - \frac{1}{2}Y^2 \sin^2 \theta \frac{1}{1 - X - iZ} \pm \frac{1}{1 - X - iZ} \left(\frac{1}{4}Y^4 \sin^4 \theta + Y^2 \cos^2 \theta (1 - X - iZ)^2 \right)^{1/2}}\]

\[
n = \text{complex refractive index},
\]
\[
X = \frac{\omega_0^2}{\omega^2}, \quad Y = \frac{\omega_H}{\omega}, \quad Z = \nu/\omega,
\]
\[
\nu = \text{electron collision frequency},
\]
\[
\omega_0 = 2\pi f_0 = \sqrt{\frac{Ne^2}{\varepsilon_0 m_e}} \quad \text{is the electron plasma (electron-ion collision) frequency}
\]
\[
\omega_H = 2\pi f_H = \frac{B_0 |e|}{m_e} \quad \text{is the electron gyro frequency.}
\]
Electron density \(n_e\), mass \(m_e\) and charge \(e\)
Magnetic field vector amplitude \(B_0\) and direction \(\theta\) relative to wave
HF Propagation and Sounding

• Measure the electron density as a function of altitude
  – Measure “tilts” in the density of ionization
  – Measure ionospheric plasma irregularities
  – Determine time variation of irregularities

• Understand propagation by ionospheric refraction or through the ionosphere from ground-to-space

• Understand energy transfer around the globe
  – Interaction with the upper atmosphere

• Understand potential impact on satellites

• Perform frequency planning for OTHR

Backscatter Observation

- Range-time-intensity plot of received power (Rx) from the Jicamarca radar facility in Peru at 12° south latitude [11]. The Jicamarca operating frequency was 49.92 MHz. These large structures are most likely due to electron-density depletion regions caused by gravitational Rayleigh-Taylor instabilities.

Oblique Ionogram Example
New Kent, VA to Bedford, MA

Vertical lines are HF comms

Note: strong, off-axis signals

- F layer, 3-hop
- F layer, 2-hop, O and X
- F layer, 1-hop, O and X
- E layer, 1-hop (?)

From: F. Robey, HFGeo Proposer's day presentation: https://www.iarpa.gov/index.php/research-programs/hfgeo/phase-1b-baa
• Delay of surface wave radars received over an ionospheric refracted path have been observed for a year to understand ionospheric dynamics
• The above plot shows a 24 hour portion of data with multiple radar sources
• CODAR sweeps are offset in time
• Variation in path delay as well as ionospheric multipath can be observed
Example: 4.82 MHz CODARS
20161025

- VSA CODAR tracker processing

- Track database created for 4.82 MHz CODAR links over a one year period
  - Angle of arrival, group delay, Doppler and polarization provided for many modes
  - A unique and long term data set for ionospheric and geolocation model development and validation
Radio propagation for communication link reliability has been of interest for many decades.

There are good tools to predict performance based on average ionospheric density parameterized by solar activity.

The primary research interests now are to understand variations from ideal and interaction with lower atmospheric layers:
- Bubbles, irregularities
- Ionospheric motion due to thunderstorms, earthquakes and other natural phenomenon

VOACAP coverage prediction near WWV frequencies

5.3MHz

14.1MHz
Outline

• Introduction to the ionosphere

• Ionospheric impacts on RF signals

• Areas for research

• Conclusion
Potential Research Topics

- EM wave propagation in plasma is relatively mature and assimilation and modeling is an active research area with many players

- Some emerging areas provide potential for limited-duration but ground-breaking applied math research

- Dual polarized multi-frequency picosats orbiting within the ionosphere
  - Enabled by low cost access to space
  - Potentially provides high horizontal resolution and with computerized tomography and other sources, high vertical resolution
  - Measures TEC within the ionospheric column
  - Electromagnetic propagation must be included in inversion
  - Potential utility of new measurements has not been studied

- Use of vector antenna for ionospheric characterization
  - Antenna first proposed in 1990, only recently made practical
  - Primarily used for direction finding of a single source, not imaging
  - Low resolution (CRB) antenna
  - Need for space-time algebraic investigation
Picosat ionospheric characterization

- **Understanding the ionosphere is key to many applications**
  - The bottom side (<90-400km) profile and stability is particularly important for many missions

- **Techniques currently used include:**
  - Vertical, Oblique, & Backscatter sounders – limited by access, ground based transmitter logistics, limited sampling
  - Dual Frequency GPS TEC measurement, space-ground or occulting – Total electron content dominated by exponential tail above the peak
  - Measurements lower in the ionosphere are needed
Space Radar Beacon Concept


Right: Kicksat from https://www.kickstarter.com/projects/zacinacation/kicksat-your-personal-spacecraft-in-space
Math Research Questions

• Waveform design is well understood

• Things that are not understood requiring primarily mathematical analysis
  – What does the addition of the ability to observe O and X modes do to assist in inversion?
    • Ability to better understand small scale structures?
    • Ability to better understand horizontal variations in electron density?
    • Frequency dependence of the utility?
  – How is the inversion performed when dual polarization measurements are added?
  – Does the math determine the receive antenna type? Do we need a dual polarization antenna, or is single polarization sufficient?
  – What are the statistical properties of the estimate?
Electromagnetic Vector Sensing

- 3 dipoles + 3 loops (electrically small)
- Measures full E and B field vectors, \( \mathbf{E} \times \mathbf{B} = \mathbf{S} \) (Poynting vector)
- Determines sources’ intensity, direction and polarization in single snapshot
- Typically used for finding direction of strong sources
- Additional degrees of freedom when compared to triad/tripole
- More sensitive (\( \geq 2x \)), capable element than tripole for interferometric arrays

A more complex receive antenna providing direction of arrival and polarization state
Signal Processing
Vector Antenna Measurements

- Measurements are time dependent vector sensor element amplitudes
  - Converted to baseband for processing
  - Angle of Arrival ($\theta_k, \phi_k$), Amplitude, and Polarization state ($\gamma_k, \eta_k$) are embedded in measurements

- The variation in antenna patterns allows estimation of physical parameters.
  - "Curvature of the array manifold"

- Spatial mapping, often called spectral estimation, or inversion is necessary to estimate source parameters

- Application specific post-processing
  - Long term statistics
  - Calibration
  - Transient event detection
Vector Antenna Signal Model

- Signal model of N-length signal vectors,
  \[ z[i] = \sum_{k} \beta_k[i] a_k + n[i] \]
  - \( z[i] \): are sampled received data vectors at baseband
  - \( \beta_k[i] \): signal amplitude
  - \( n[i] \): are received noise sample vectors (stochastic Gaussian)
  - \( i \): is the sample index
  - \( K \): number of sources
  - \( a_k \): array response “steering vectors”

\[
\mathbf{a}_k \equiv \mathbf{a}(\theta_k, \phi_k, \gamma_k, \eta_k) \equiv \begin{bmatrix} e_{xk} \\
e_{yk} \\
e_{zk} \\
h_{xk} \\
h_{yk} \\
h_{zk} \end{bmatrix} = \begin{bmatrix} \cos \phi_k \cos \theta_k & -\sin \phi_k \\
\sin \phi_k \cos \theta_k & \cos \phi_k \\
-\sin \theta_k & 0 \\
-\sin \phi_k & -\cos \phi_k \cos \theta_k \\
\cos \phi_k & -\sin \phi_k \cos \theta_k \\
0 & \sin \theta_k \end{bmatrix} \begin{bmatrix} \sin \gamma_k \ e^{j\eta_k} \\
\cos \gamma_k \end{bmatrix}
\]

- \( R = E\{z[i]z^H[i]\} = \sum_{k=1}^{K} \gamma a_k a_k^H + \sigma^2 \mathbf{I} \)
  - \( \sigma^2 \): is the receiver noise power
  - \( \gamma_k \): is the received power of the k’th source

Vector Sensor Inversion Processing

Measurements $\rightarrow$ Spatial Mapping “Inversion” $\rightarrow$ Application Specific Post Processing

Linear projection:

$$\hat{P}(\theta_i, \phi_i, \gamma_i, \eta_i) = \sum_t |z^H(t)a(\theta_i, \phi_i, \gamma_i, \eta_i)|^2$$

Super-resolution Maximum-Likelihood:

$$\hat{\Sigma}^{p+1} = \text{diag}(\hat{\Sigma}^p + \hat{\Sigma}^p A^H (\hat{R}^{-1}_p S \hat{R}^{-1}_p - \hat{R}^{-1}_p) A \hat{\Sigma}^p)$$

$$\hat{R}^{p+1} = A \hat{\Sigma}^{p+1} A^H + \sigma^2 I$$

$$S = \frac{1}{M} \sum_{i=1}^M z[i]z^H[i]$$

columns of $A$ are the $a(\theta_i, \phi_i, \gamma_i, \eta_i)$
diagonal terms of $\hat{\Sigma}$ are estimates of $$\hat{P}(\theta_i, \phi_i, \gamma_i, \eta_i)$$

- Invert measurements to spatial map
  - Intensity and polarization as a function of angle of arrival, frequency, and time
  - Sources are a combination of discrete and diffuse signals

- Algorithm development challenges
  - Extremely ill conditioned
  - Computationally intensive
  - Diffuse signals have low SNR

Algorithm development is needed
Imaging Algorithms

• Initial study is development of imaging algorithms for **single vector sensor**
  – Imaging of distributed sources
  – Resolution of discrete sources

• Initial results with distributed sources illustrate ambiguity of ML estimator

• Need to develop algorithms
  – Higher order statistics: increase number of detectable sources
  – ‘Pixel’ estimation vs. spherical harmonic coefficient estimation
Range Doppler Mode Identification

Results generated by Naval Research Laboratory
Radar Waveform - 20kHz Swept BW, 10Hz WFR, 10s Dwell, 5.48MHz fc, E3 → N

Range Doppler Plot H1 EMVS2

Data Collected by Naval Research Laboratory

INTELLIGENCE ADVANCED RESEARCH PROJECTS ACTIVITY (IARPA)
2D EMVS Array Spatial, Polarization Processing

Range Doppler Plot H1 EMVS2

Tx 1 Left Circular Polarization

Est. ~176°Az, 69°El

These results were generated by Naval Research Laboratory

Tx 1 Skywave

Tx 3 Ground Wave

Est. ~169°Az, 0°El

Radar Waveform - 20kHz Swept BW, 10Hz WFR, 10s Dwell, 5.48MHz fc, E3 → N

2012-03-03 023320 UTC
Conclusion

- Radars are heavily used to understand the earth’s ionosphere
  - Passive radar using GPS as the source
  - Sounding by active transmitters
  - Passive bottom-side reception

- Radar measurements are typically inverted to determine an ionospheric model consisting of electron density in voxels

- Examples of the variation in electron density on signals passing through the ionosphere were shown. Significant effects can be observed.