High Frequency Radars and Ionospheric Sounding

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For:
University Of Colorado
Aerospace Engineering Sciences
ASEN 5245
26 April 2011

In Cooperation with:
National Oceanic and Atmospheric Administration
National Geophysical Data Center
Solar and Terrestrial Physics Division
Outline

- System
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  - Ionosphere
  - Propagation in Plasma
  - Antennas
  - Radar Equation
- Signal Processing
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  - Polarization
  - Doppler
  - Interferometry

- Research
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  - Plasma Physics
  - Geophysics
  - Waves
  - Turbulence
  - Meteors
- System Performance
What is an Ionosonde and what does it do?

- MF-HF Radar (1-20 MHz)
- A acre or ten of antennas
- Measures ionosphere reflection height at a precise density (sounding frequency)
- Feature recognition software needed in an often complex image
- Inversion process required to obtain bottom-side electron density profile
- Valleys and Topside are modeled or extrapolated
Ionosonde History

- The first radar, invented in 1926
- Used to measure the height of the ionosphere
- Bi-static “chirp” and mono-static “pulse” varieties
- Longest ionosphere climate record
- ~ 100 Vertical Incidence ionosondes worldwide
- New technologies have evolved the ionosonde:
  - High power solid state transmitters
  - Data display and recording
  - Antennas and antenna modeling
  - Computers and data handling
  - Digital Signal Processing
Earth's Ionosphere

- Plasma of ionized atmospheric gases
  - NO, O2, O, H, He
- Produced by solar EUV (mostly)
- ~50 to ~1000 km altitude
- Strong temporal variations
  - Daily
  - Seasonal
  - Solar Cycle
- Strong interaction with Earth's magnetic field
  - Solar produced magnetic disturbances
  - High, Middle and Low Latitudes
Ionosondes Measure Up To $H_{\text{max}}$

The F2 region varies by 3-5X diurnally, highest just after noon, lowest before dawn.

The F1 region and E region dissipate at night.

The D region is present only during daytime and in times of high activity.
Radio Waves in Plasmas

Plane Wave Electric Field

\[ E(z) = \Re \left( E_o e^{i(\omega t - kz)} \right) \]

Index of Refraction

\[ n = \frac{ck}{\omega} = (\mu - i\chi) \]

- Cool plasma
- No Collisions
- No Magnetic Field

\[ \mu^2 = 1 - X = 1 - \frac{f_N^2}{f^2} = 1 - \frac{\kappa N}{f^2} \]

\[ \kappa = \frac{e^2}{4\pi^2 \epsilon_0 m} \approx 80. \]

Propagation near the speed of light when \( f_N \ll f ; \mu \approx 1 \)

Propagation slows dramatically when \( f_N \rightarrow f ; \mu \rightarrow 0 \)

Specular (total) reflection occurs when \( f_N = f ; \mu = 0 \)

After Davies, 1965
A magneto-plasma is birefringent
The index of refraction depends on the polarization of the radio wave

A magneto-plasma is anisotroptic
The index of refraction depends on the direction of propagation

Index of refraction:
\[ \mu^2 = 1 - \frac{2X(1 - X)}{2(1 - X) - Y_T^2 \pm \sqrt{Y_T^4 + 4(1 - X)^2 Y_L^2}} \]

With respect to the direction of propagation:
\[ Y_L = \text{Longitudinal component of } \bar{Y} \]
\[ Y_T = \text{Transverse component of } \bar{Y} \]

The + and – refer to the Ordinary and Extraordinary polarized radio waves

Reflection occurs when
\[ f_N = f \] (Ordinary wave)
\[ X = 1 - Y \] (eXtraordinary waves)
\[ X = 1 + Y \]

O&X are circularly polarized over most the Earth
Linearly polarized at the magnetic equator

After Davies, 1965
The full Appleton equation with collisions

\[ Z = \frac{f_v}{f} \]

\[ n^2 = 1 - \left( 1 - \frac{X}{2(1-X-iZ)} \right) \pm \sqrt{\frac{Y_T^4}{4(1-X-iZ)} + Y_L^2} \]

With propagation below 30 MHz in the Earth's ionosphere, all of these factors can substantially influence the radio wave.

This influence provides both Great Opportunity and Great Difficulty with Remote Sensing and Radio Science with Ionosondes.

After Davies, 1965
Phase and Group Velocity

Phase velocity is defined as:  \( v = \frac{c}{\mu} \)  \( \therefore v = c \to \infty \)  as  \( \mu = 1 \to 0 \)

Which means the radio wavelength increases in a plasma

Group velocity is:  \( u = \frac{d \omega}{d k} \)  \( u = c \to 0 \)  as  \( \mu = 1 \to 0 \)

Which means the propagation speed decreases in a plasma

Group Refractive Index is:  \( \mu' = \frac{c}{u} = c \frac{d k}{d \omega} = \mu + f \frac{d \mu}{d f} \)

With no magnetic field:  \( \mu' = \frac{1}{\mu} \)  \( \therefore \mu' = 1 \to \infty \)  as  \( \mu = 1 \to 0 \)

After Davies, 1965
Virtual Height and Density Profiles

- Ionosondes measure the time of flight of a packet of radio frequency energy
- Virtual Height or Group Path
- Integral of the Group Refractive Index

Virtual height

$$h'(f) = \int_0^{h_g} \mu'(f) \, dh$$

For a parabolic electron density profile:

$$N(h) = \frac{f_p^2}{80.5} \left[ 1 - \left( \frac{h - h_o}{y_m} \right)^2 \right]$$

Virtual Height (reflection):

$$h'(f) = h_o - y_m + \frac{y_m}{2} \frac{f}{f_p} \ln \frac{f + f_p}{f_p - f}$$

Virtual Height (through the layer):

$$h'(f) = h_o - y_m + y_m \frac{f}{f_p} \ln \frac{f + f_p}{f - f_p}$$

After Davies, 1965

(no magnetic field)
Parabolic EDP and Virtual Height

Virtual Height Example

\[ h'(0.834f_0F_2) = h_mF_2 \]
Propagation through a Layer

Virtual Height Example

- $h'(f)$
- Electron Density Profile

- $h_mE$
- $f_0E$

Frequency [MHz]

Height [km]
Ionogram Movie

Ionogram sweeps 20 seconds long every minute shows quiet-time mid-latitude dynamics
Research Ionosonde: Wallops Island, USA

Vertical Incidence Pulsed Ionospheric Radar (Dynasonde)

Transmit Antenna

Receive Array
VIPIR Radar Features

- Very high interference immunity: IP3 > 40 dBm
- High Dynamic Range: 115(I) +30(V) dB
- Direct RF sampling 14 bits at 80 MHz
- Fully digital conversion, receiver and exciter
- Waveform Agility: 2 µs to 2 ms pulse/chip width
- USB-2 Data and Command/Control Interfaces
- 8 coherent receive channels; Frequency: 0.3 – 25 MHz
- 4 kW class AB pulse amplifier: 3rd harmonic < -30 dBc
- Precise GPS timing for bi-static operation
- Radar software Open Source C code; runs under Linux

Designed for extreme performance and flexibility
Transmit Antenna Performance

Wallops ZZLPA FOM: 29.054  7.681  5.990

- Vertical Gain
- Right Circular
- Left Circular
- SWR

Vertical Gain [dBi]

Frequency [MHz]

SWR
Typical Transmit Antenna Pattern
Receive Antennas

4m dipoles, 5m high
Atmospheric Noise Factor at HF

- Noise below 30 MHz is dominated by atmosphere and man-made sources

\[ F_a \text{ versus frequency (}10^4 \text{ to } 10^8 \text{ Hz)} \]

- **A)** Atmospheric 99.5%tile
- **B)** Atmospheric 0.5%tile
- **C)** Man-made (Quiet)
- **D)** Galactic
- **E)** Man-made (City)

\begin{align*}
At \lambda = 300m & \quad F_a \approx 70dB \\
At \lambda = 100m & \quad F_a \approx 50dB \\
At \lambda = 15m & \quad F_a \approx 30dB
\end{align*}

Source: ITU-R P.372-10 (2009)
Total Specular Reflection

The ionosphere spectacularly reflects “all” of the incident energy
The power density at the ground is equivalent to that at Range = 2H

\[ P_d = \frac{P_t G_t}{4\pi H^2 L_t} \]

\[ P_d = \frac{P_t G_t}{8\pi R^2 L_t} \]
Radar Equation for Ionosondes

**Signal**

\[ S = \frac{P_t G_t}{8 \pi L_t R^2} \frac{1}{L_p} \frac{\lambda^2 G_r}{4 \pi} \]

Ignoring propagation losses

\[ S = \frac{P_t G_t G_r (\frac{\lambda}{R})^2}{32 \pi^2} \]

\( P_t \approx 1 \text{ kW} = +60 \text{ dBm} \)

\( G_t \approx G_r \approx 3 \text{ dB} \)

\( S \approx 10 (\frac{\lambda}{R})^2 [W] \)

**Noise**

\[ N = k T_0 B F_n F_a \]

\( B = 15 \text{ kHz} \)

\( F_n \approx 6 \text{ dB} \quad \text{Active Preamp} \)

\( F_a \approx 70 \text{ dB} \quad \text{At} \, \lambda = 300 \text{ m} \)

\( F_a \approx 50 \text{ dB} \quad \text{At} \, \lambda = 100 \text{ m} \)

\( F_a \approx 30 \text{ dB} \quad \text{At} \, \lambda = 15 \text{ m} \)

\( k T_0 B F_n = -124 \text{ dBm} \)

Bandwidth decision is a complex tradeoff between radar resolution, dispersion in the ionosphere and spectrum usage.
SNR Examples (20 and 3 MHz)

- **R=100 km, \( \lambda=15m \) (20 MHz)**
  - \( S=-66\, \text{dBm} \); \( N=-96\, \text{dBm} \); \( \text{SNR}=+30 \, \text{dB} \)
- **R=400 km, \( \lambda=15m \) (20 MHz)**
  - \( S=-78\, \text{dBm} \); \( N=-96\, \text{dBm} \); \( \text{SNR}=+17 \, \text{dB} \)
- **R=100 km, \( \lambda=100m \) (3 MHz)**
  - \( S=-50\, \text{dBm} \); \( N=-76\, \text{dBm} \); \( \text{SNR}=+26 \, \text{dB} \)
- **R=400 km, \( \lambda=100m \) (3 MHz)**
  - \( S=-62\, \text{dBm} \); \( N=-76\, \text{dBm} \); \( \text{SNR}=+14 \, \text{dB} \)

For sites with “reasonable” noise, very high SNR can be obtained with “modest” antennas.
SNR Example (1 MHz)

- Antenna gains are no longer constant
  - Transmit antenna is small and inefficient (-7 dBi)
  - Receive antenna is close to the ground (-15 dBi)
- \( R=100 \text{ km}, \lambda=300\text{m} \) (1 MHz)
  - \( S=-62 \text{ dBm} ; N=-56 \text{ dBm} ; \text{SNR}=-6 \text{ dB} \)
- \( R=400 \text{ km}, \lambda=300\text{m} \) (1 MHz)
  - \( S=-75 \text{ dBm} ; N=-56 \text{ dBm} ; \text{SNR}=-19 \text{ dB} \)

Even “large” antennas become electrically small at low frequencies. Inefficiencies and atmospheric noise take over.
Other spectrum users often set the “noise” level
Modern Data Analysis

Data Analysis Techniques for use on Modern Ionosondes
Analysis Background

- High SNR values allow for several options
  - Build a small and/or cheap radar
  - Integrate / pulse compress to get your SNR back
- Build a good radar and exploit the opportunities
  - Stable single-pulse statistics
  - Precision techniques
  - Rapid measurements
  - Discovery
Ionosondes: Reversed Independent Variables

- With most radars, the observation location is selected by the instrument
  - Radar look direction, antenna beam pattern
- The target is measured
  - Radar Reflectivity
  - Range
- With an ionosonde, the plasma density is set by the frequency of observation.
- Virtual range (Time-of-flight) is measured
- The measurement is derived
  - Location (true range, direction) of the ionosphere which has that density.
Precision vs Resolution

- Resolution is the ability to separate 2 objects
  - Closely spaced in some dimension (i.e. Range)
  - Determined by waveform (bandwidth)
- Precision is the ability to measure a resolved object
  - Mostly determined by SNR
Impulse Response Fitting

San Juan SJJ18 2010 264 18:50 UT

Data
O
X

Amplitude [dB]

Range Gate

Ao=58.6 ; Ro=166.7
Ax=53.3 ; Rx=176.9

Precision is about 0.1 range gate (150m)
Depending on SNR and echo separation
Polarization

- Ordinary and eXtraordinary polarizations are circular and of opposite rotation
  - Except very near the magnetic equator, it is linear
- Two orthogonal, linearly polarized antennas can form a circularly polarized antenna
  - Some ionosondes can not
  - Digisondes do this in hardware at the antenna
  - VIPIR and Dynasonde do this in the analysis software

San Juan, Puerto Rico
Polarization Example: VIPIR

- Two orthogonal antennas
- Separate receivers
- O and X mode signals
- Range resolved
- Magnitude [dB]
- Phase [deg]
- -90 for O-mode
- +90 for X-mode
Doppler is the first moment of the phase vs time observation.

- Doppler
- Higher order moments?
Interferometry

- The phase difference between spaced antennas related to the angle of arrival of a plane radio wave

- Issues:
  - $2\pi$ ambiguity
  - Non-plane wave
  - Mutual Coupling
  - Multiple spacings aid to resolve this problem
  - Room for Improvement

\[
\phi_2 - \phi_1 = |\vec{k}| D \sin(\theta)
\]
SPGR

- The virtual height of the ionosphere can be measured using the phase differences between two closely spaced frequencies.
- The result is called Stationary Phase Group Range or Precision Group Height.
- Assumes the actual height of reflection is constant:
  - Can be relaxed by using multiple values of $\Delta f$
- Subject to $2\pi$ ambiguities.
- Subject to Doppler shift.
- Range precision becomes related to phase precision: $h' = \frac{c}{4\pi} \frac{\Delta \phi}{\Delta f} \rightarrow 100$ m
Recommended areas of research using modern ionosondes

“If we knew what we were doing, it wouldn’t be research” – Einstein
Applications of the Modern Ionosonde

Wright & Bullett

Auto-Processed Ionosonde Ionogram

N(h) profiles
Phase Structure Functions
To all products

Atmospheric Gravity Waves
Deterministic Description
Daily Summary

Mid-Scale Irregularities

Special Indices
Sunrise [O]/[N₂]
D-Region
S₂, S₃, Scintillations
Δf/f → ΔN/N

Small-Scale Irregularities

Vector Velocities
Radio Absorption

Electric Fields

Geomagnetic Storms

Communication Forecasts

Thermospheric & Ionospheric Models:
All boxes contribute

Scintillation Models

Eddy Mixing: Turbopause

Auroral Precipitation

Radio foF₂, foE, M3k

Basic Physics of Radio Waves in Magneto-Plasma

RF Heating experiments

Internal Content per Echo:
Precision Echolocation, Doppler, Polarization, Amplitude, high-resolution phase path, and more.
Plasma Physics with Ionosondes

- Careful examination of changes in transmitted radio wave properties:
  - Amplitude, Range, Frequency, Doppler, Direction, Phase
- Determine the plasma properties
  - Densities
  - Waves
  - Turbulence
  - Structure
  - Composition
- Physical Processes
  - Natural
  - Artificial
Geophysics with Ionosondes

- Derive physical quantities from the ionosonde data
  - Electron Density Profiles
  - Vector Velocities
- Study Ionosphere and Thermosphere physics
  - Photochemistry
  - Ion & Neutral Composition
  - Electric Fields
  - Neutral Winds
  - Coupling and Energy Transport
  - Short and long term variability
  - Forecasting
Boulder 1-minute Data

Note activity in the afternoon near 4MHz
Very Fast Sweeps

- Ionogram sweeps < 10 seconds long
- Continuous repeat of 100's of sweeps possible

What will these data reveal?
Plasma Turbulence

Smooth E- layer

Structured E- layer

Cause?
V_{los} = 41 \text{ m/s}
E-region studies

Source of these echoes?
Science and Engineering Needs

- Improved dynamic range → 16 bit ADC
- Greater data bandwidth → USB3
- More Digital Filters
- Manual Ionogram Analysis Software
- Echo Detection and Parametrization
- Improved Ionogram Scaling
- Amplitude and Phase Calibrations
- Improved data collection → continuous
- Super-resolution direction finding & plasma imaging
- Interference removal
Questions?

Space Weather?
Internet Resources

- World Data Center A, Boulder:  
  http://www.ngdc.noaa.gov/stp/IONO/ionohome.html
- Digisondes and ARTIST:  
  http://ulcar.uml.edu/
- Autoscala:  
  http://roma2.rm.ingv.it/en/facilities/software/18/autoscala
- ESIR:  
  http://www.spacenv.com/
- Dynasonde21:  
  Nikolay.Zabotin@colorado.edu
- Low-latitude Ionospheric Sensing System:  
  http://jro.igp.gob.pe/lisn/
- Vertical Incidence Pulsed Ionosphere Radar (VIPIR):  
  Terry.Bullett@noaa.gov
- Canadian Advanced Digital Ionosonde (CADI):  
  http://cadiweb.physics.uwo.ca/
- Ionospheric Prediction Services (IPS):  
- Ionosonde Network Advisory Group (INAG)  
- SPIDR:  
  http://spidr.ngdc.noaa.gov/spidr/index.jsp
Credits

- University of Colorado
- NOAA National Geophysical Data Center
- NASA Wallops Island Flight Facility
- US Geological Survey
- US Air Force Research Laboratory
- Scion Associates
- University of Massachusetts Lowell
- All ionosonde data producers who freely share their data!