TID Study in Antarctica: First Results from New Instruments

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Outline

- Challenges of GNSS studies in Antarctica
- Interferometric methods
- TID study with GNSS TEC in Antarctica
- Sensitivity of GNSS TEC (vs HF Observations)
- Latest HF results from Antarctica
- Summary

Which way do we go again? Just follow the GPS!
GPS TEC observations in Antarctic Peninsula region

Drake Passage in Antarctica generates severe tropospheric waves, i.e., it is associated with cyclones, convective plumes, enhanced zonal winds, orographic waves, etc.

2009-2012

65 deg South geographically
~51 deg South geomagnetically
Simulation of tropospheric Gravity Waves propagating to ionospheric heights

(D. Fritts)

Secondary GWs (moving left) and acoustic waves (circular patterns at right above ~100 km) above strong mountain wave breaking in tidal shears at ~80 km
USA vs Antarctic Peninsula 1925 : 15
GNSS interferometry methods

(Wan et al., 1997; Afraimovich et al., 1998; Hernandes-Pajares, 2006; Galushko et al., 2014 and others.)

\[
\omega' = \omega - k_x (\omega)V_{IPPx} - k_y (\omega)V_{IPPy} \Rightarrow \omega - \Delta \omega
\]
Interferometry for arbitrary shape of the disturbance

For any disturbance represented as

\[ I(x, y, t) = I(x \sin \alpha + y \cos \alpha - Vt) \]

Solution is:

\[
\sin \alpha(t) = \gamma_x(t) / \sqrt{\gamma_x^2(t) + \gamma_y^2(t)}
\]

\[
V(t) = \frac{1}{\gamma(t)} \left[ \gamma_x(t) \frac{dx_p(t)}{dt} + \gamma_y(t) \frac{dy_p(t)}{dt} - I'(t) \right]
\]

Where space and time derivatives are:

\[
I'(t) = dI(x, y, t) / dt
\]

\[
\gamma_x(t) \equiv \partial I(x, y, t) / \partial x
\]

\[
\gamma_y(t) \equiv \partial I(x, y, t) / \partial y
\]

Derivatives can be numerically calculated

\[
I'_1(t_n) \approx \frac{I_1(t_n) - I_1(t_{n-1})}{\Delta t}
\]

\[
\gamma_x(t_n) \approx \frac{y_3 \cdot (I_2(t_n) - I_1(t_n)) - y_2 \cdot (I_3(t_n) - I_1(t_n))}{x_2y_3 - x_3y_2}
\]

\[
\gamma_y(t_n) \approx \frac{x_2 \cdot (I_3(t_n) - I_1(t_n)) - x_3 \cdot (I_2(t_n) - I_1(t_n))}{x_2y_3 - x_3y_2}
\]

[Galushko et al., 2016]
Data analysis constraints

Correlation coefficient between TECs from different stations:

\[ K_{ij} \geq 0.5 \]

To assure accuracy in azimuth calculation of better than 10 deg for the given GNSS station geometry it is necessary to satisfy:

\[ |\gamma| \geq 15 \cdot 10^{-4} \quad \text{[TECu/km]} \]

Elevation angle > 30 deg

Data availability: April 2009 to June 2012
Strong correlation between TID occurrence and the solar terminator. In the mid-year (winter) TIDs are present only during the daytime and are apparently generated by the solar terminator passage over the observation point. During the other half of the year, TIDs are present most of the time, with the exception of the period around 20 UT (~16 LT) when a minimum in peak electron density is observed at that location. Apparently, during that time, there is not enough plasma to support TIDs.
Measurements taken from Vernadsky ionosonde for years 2010-2011. Plasma density distribution is shown by critical frequency, foF2.
“Perfect anti-match” between measured TID azimuth and modeled neutral wind direction (dots). The neutral wind is calculated with TIEGCM model for several quiet days in Jan-Apr 2011. In the figure the direction of the neutral wind is shifted by 180 deg, thus showing the “anti-windward” direction. Quiet-time TID measurements for the entire period of observations (2009-2012) are shown. Note that several TID modes are present simultaneously: one with changing azimuth and at least two others with constant azimuthal directions of about -50 deg and 150 deg.
Gravity waves tend to propagate in the anti-windward direction

The so-called wind filtering effect

Daily trends of TID direction (geographic azimuth) measured at Antarctic Peninsula during 2009-2012. Note that the disturbances observed during the disturbed periods predominantly propagate North and North-West, i.e., equatorward. Disturbances observed during the quiet time change azimuthal direction during the day, i.e., follow the anti-windward direction.
Are these TIDs?

Changes in virtual height... due to ...progression of a wave motion of such nature as to cause changes in ion concentration (for example, a pressure wave). [Munro, 1948]

..the reason for the repetition of small changes in region F2 ..a rapid east-west motion of or within region F2 ionization...[Beynon, 1948]

**Quasi-periodic variations in the ionosphere:** [e.g. Ogawa et. al., 1987]
- Period: 15-90 min
- Velocity: 100-250 m/s
- Horizontal wavelength: 100-1000km

**Origin:** AGWs [Hooke, 1968] or F region instability [Perkins, 1973].
How sensitive are TEC measurements, especially during the night time?
HF and GPS Data Comparison

January 26, 2014

[Graph showing TECu and Height, km over UT from 18 to 23, with two sets of data represented by different symbols and line styles.]
HF and GPS Data Comparison

January 19, 2014 (Cherry)

- **dTEC**
- **AoA elevation**

**UT**

- **dTEC**
- **AoA**

**Height, km**

**January 19, 2014 (Cherry)**

- **Δf0F2**
- **dTEC**

**AoA E (POL)**

NSF
HF and GPS Data Comparison

Sept 12, 2014

- Ratio of responses on GPS and HF varies significantly
- Note large GPS signature at 19:00 corresponds to relatively modest signature on HF; conversely, at 21:00 HF response exceeds GPS
Disturbances in the ionosphere (e.g., TIDs) affect the propagation of the HF radio waves. By measuring the parameters of the ionospherically reflected HF signal it is possible to monitor and to measure the characteristics of TIDs.

Antarctic TID study Project

Project Timeline

- 2012: GNSS Measurements become available
- June 2015: Single channel HF radar is installed
- October 2015: Three channel HF system is installed
- January 2016: First HF data is delivered to Boston College
- February 2016: Routine HF observations at Vernadsky started
- September 2016: Multifrequency upgrade is designed
• Built and installed three-channel HF receive system to measure AoA and Doppler
• Also installed Septentrio GNSS receiver
• Raw data shipped by sea, first significant data delivery made in January 2016
USRP N210 system

**USRP™ N200/N210 NETWORKED SERIES**

**FEATURES:**
- Use with GNU Radio, LabVIEW™, and Simulink™
- Modular Architecture: DC-6 GHz
- Dual 100 MS/s, 14-bit ADC
- Dual 400 MS/s, 16-bit DAC
- DDC/DUC with 25 MHz Resolution
- Up to 50 MS/s Gigabit Ethernet Streaming
- Fully Coherent MIMO Capability
- Gigabit Ethernet Interface to Host
- 2 Gbps Expansion Interface
- Spartan 3A-DSP 1800 FPGA (N200)
- Spartan 3A-DSP 3400 FPGA (N210)
- 4 MB High-Speed SRAM
- Auxiliary Analog and Digital I/O
- 2.5 ppm TCXO Frequency Reference
- 0.01 ppm w/ GPSDO Option

**N200/N210 PRODUCT OVERVIEW:**
The Ettus Research™ USRP™ N200 and N210 are the highest performing class of hardware of the USRP™ (Universal Software Radio Peripheral) family of products, which enables engineers to rapidly design and implement powerful, flexible software radio systems. The N200 and N210 hardware is ideally suited for applications requiring high RF performance and great bandwidth. Such applications include physical layer prototyping, dynamic spectrum access and cognitive radio, spectrum monitoring, record and playback, and even networked sensor deployment.

The Networked Series products offers MIMO capability with high bandwidth and dynamic range. The Gigabit Ethernet interface serves as the connection between the N2000/N210 and the host computer. This enables the user to realize 50 MS/s of real-time bandwidth in the receive and transmit directions simultaneously (full duplex).

<table>
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<td>Frequency Accuracy</td>
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<td>ppm</td>
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</table>

| **RF PERFORMANCE (W/ WBX)** | | |
| SSB/LO Suppression | 35/50 | dBc |
| Phase Noise (1.8 GHz) | | |
| 10 kHz | -80 | dBc/Hz |
| 100 kHz | -100 | dBc/Hz |
| 1 MHz | -137 | dBc/Hz |
| Power Output | 15 | dBm |
| IIP3 | 0 | dBm |
| Receive Noise Figure | 5 | dB |

| **PHYSICAL** | |
| Operator Temperature | 0 to 55° | C |
| Dimensions (L x W x H) | 22 x 16 x 5 | cm |
| Weight | 1.2 | kg |

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Left: three antenna array installed at Palmer station. Distance between the antenna pairs is approximately 25 meters, and antennas are leveled to 1-2 cm accuracy.
Right: Antenna #2 close-up photo and curious native.
Transmitter assembly at Vernadsky station. The system includes ICOM-718 transceiver, antenna tuner, power supply box, modulator, and PC computer. Operational power 10-50 W.
Simultaneous observations at two locations

Vernadsky (vertical)

Palmer (oblique)
TID disturbance is detected from the recorded signal spectrum (left). Then a FFT is taken with a sliding window, resulting in another spectrogram (right). Intensity of TID can be estimated as a sum of several spectral lines (white curve in the left plot).
intensity of TIDs as measured by bystatic HF sounder at different frequencies. Note that measurements at the two highest frequencies have approximately same intensities, indicating a possible presence of the maximum of in the vertical profile of TID amplitudes.
Occurrence probability from HF measurements. During HF measurements confirm the pattern observed with the TEC data (Figure 1). During the nighttime (5-9 UT) the TIDs are observed only about 30%, while during the day they are typically observed 70-80% of the time.
Calculating TID parameters with “FAS” approach

- Use bistatic (or vertical) HF measurements of trajectory signal parameter variations (AoA+Doppler) to determine TID parameters

- Advantages:
  Cheap, simple, transmitters of opportunity can be used

- Disadvantages:
  Essentially a single-point measurement; inversion of spatial TID parameters requires simplified TID model; high accuracy of AoA and Doppler required.

Digisonde observations of TIDs with frequency and angular sounding technique, Paznukhov, V. V.; Galushko, V. G.; Reinisch, B. W., 2012, Advances in Space Research, Volume 49, Issue 4, p. 700-710.
Oblique FAS: geometry

Reflection conditions:

\[(\mathbf{r}_1 + \mathbf{r}_2) \cdot \hat{t} = 0\]
\[(\mathbf{r}_1 \times \mathbf{r}_2) \cdot \hat{t} = 0\]

\[f_D = -\frac{1}{\lambda_0} \frac{d}{dt} (|\mathbf{r}_1| + |\mathbf{r}_2|)\]

\[L = L_0 + L_1 = |\mathbf{r}_1| + |\mathbf{r}_2|\]

\[\hat{t} = t / |t|\]

\[t = \partial h / \partial x \hat{x} + \partial h / \partial y \hat{y} - \hat{z}\]

\[\gamma_x = \partial h / \partial x\]
\[\gamma_y = \partial h / \partial y\]

Surface spectral representation:

\[h(x, y, t) = \int_{-\infty}^{\infty} N(\Omega) e^{i\Omega t} d\Omega e^{-iK(\Omega)(x \cos \theta(\Omega) + y \sin \theta(\Omega))}\]

\[N(\Omega)\] – amplitude
\[K(\Omega)\] – wavenumber
\[\theta(\Omega)\] – direction of motion
Reflection conditions in cartesian coordinates

\[
\frac{x_y y_x + y_z y_y - z_s}{r_1} = \frac{(x_s - D)y_x + y_z y_y - z_s}{r_2}
\]

\[y_s + z_s y_y = 0\]

\[f_D = -\frac{1}{\lambda_0} \frac{d}{dt} (r_1 + r_2)\]

Linearized, solved for \(\varepsilon, \varphi, f_D\)

\[\varepsilon(t) = h(x, y, t) \sin \varepsilon_0 \cos \varepsilon_0 + H_0 \frac{\partial h(x, y, t)}{\partial x}\]

\[\varphi(t) = -H_0 \frac{\partial h(x, y, t)}{\partial y} \tan \varepsilon_0\]

\[f_D(t) = -\frac{4H_0 \sin \partial h(x, y, t)}{\lambda} \frac{\partial t}{\partial t}\]

Measured signal parameters:

\(\varepsilon(t)\) elevation angle

\(\varphi(t)\) azimuthal angle

\(f_D(t)\) Doppler shift

Spectral representations:

\[\varepsilon(t) = \int S_\varepsilon(\Omega) e^{i\Omega t} d\Omega\]

\[\varphi(t) = \int S_\varphi(\Omega) e^{i\Omega t} d\Omega\]

\[f_D(t) = \int S_F(\Omega) e^{i\Omega t} d\Omega\]
FAS solution

With the use of the spectral representation, one gets solutions

Trajectory parameters spectra: (AoA and Doppler)

\[ S_\varepsilon(\Omega) = N(\Omega)[\sin \varepsilon_0 \cos \varepsilon_0 - iH_0 K(\Omega) \cos \theta(\Omega)] \]
\[ S_\phi(\Omega) = iH_0 K(\Omega) N(\Omega) \tan \varepsilon_0 \sin \theta(\Omega) \]
\[ S_F(\Omega) = -2iH_0 \Omega N(\Omega) \sin \varepsilon_0 / \lambda \]

Reflecting surface spectra: (TID parameters)

\[ N(\Omega) = \frac{i\lambda S_F(\Omega)}{2H_0 \Omega \sin \varepsilon_0} \]
\[ \tan \theta(\Omega) = -\frac{2H_0 \Omega \Re S_\phi(\Omega)}{2H_0 \Omega \Re S_\varepsilon(\Omega) \tan \varepsilon_0 + \lambda \Im S_F(\Omega) \sin \varepsilon_0} \]
\[ K(\Omega) = -\frac{2\Omega \Im S_\phi(\Omega) \cos \varepsilon_0}{\lambda \Im S_F(\Omega) \sin \theta(\Omega)} \]

Ratios between complex and real parts allow testing a hypothesis of a presence of idealized TID in the data.
Example of very close match between HF and GNSS observations

<table>
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<th>TEC measurements</th>
<th>HF data</th>
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<td>PRN03</td>
<td>PRN32</td>
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<td>T, [min]</td>
<td>27-35</td>
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<tr>
<td>$\alpha$</td>
<td>175°</td>
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<td>$V_m$, [m/s]</td>
<td>98</td>
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<tr>
<td>$\Lambda$, [km]</td>
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</table>
Typical HF measurements, three signal parameters

Doppler, Hz

Azimuth, deg

Elevation, deg

Time, sec, x10
First FAS results

Period of waves

December 2015 - March 2016
Direction of TID propagation

January - March 2016

Azimuth, deg

Count
Summary

• Climatology of ionospheric disturbances in Antarctic Peninsula region is controlled by neutral wind and solar terminator

• TEC observations provide a good tool for AGW/TIDs studies.

• HF observations of the bottomside ionosphere will help revealing details of TID generations and propagations and their relationship with the AGWs and tropospheric processes in general.

• How unique is this Antarctic pattern?
Thanks for your attention!