IONOSPHERIC IRREGULARITIES PREDICTIONS AND PLUMES CHARACTERIZATION FOR SATELLITE
DATA VALIDATION AND CALIBRATION

Eurico De Paula
FUNCATE - FUNDACACAO DE CIENCIAS

03/14/2014
Final Report
REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing this collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.

1. REPORT DATE (DD-MM-YYYY)  27-01-2014
2. REPORT TYPE  Final
3. DATES COVERED (From - To)  Sep 2010 - Dec 2012

4. TITLE AND SUBTITLE
Ionospheric Irregularities Predictions and Plumes Characterization for Satellite Data Validation and Calibration

5a. CONTRACT NUMBER
Ionospheric Irregularities Predictions and Plumes Characterization for Satellite Data Validation and Calibration

5b. GRANT NUMBER
FA9550-10-1-0564

5c. PROGRAM ELEMENT NUMBER

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

6. AUTHOR(S)
De Paula, Eurico R.

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Institute for Space Research - INPE
Fundação de Ciências, Aplicações e Tecnologia Espaciais,
Av. Dr. João Guilhermino, 429/11 - São José dos Campos,
São Paulo, Brasil 12210-131

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AFOSR/IOS
875 North Randolph Street
Suite 325, Room 3112
Arlington VA 22203

10. SPONSOR/MONITOR'S ACRONYM(S)
FUNCATE

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
Unclassified

13. SUPPLEMENTARY NOTES

14. ABSTRACT
During the above period the following activities were developed:
- The ionospheric plumes were characterized for 3 longitudinal sectors (east of Brazil, Peruvian coast and pacific zone) using VHF radars and algorithms were developed to represent the plumes in function of solar flux.
- The GPS signal during ionospheric irregularities was analyzed and the effect of the decorrelation was established, the variability of amplitude scintillation pattern was studied and a model alpha-Mi for the scintillation amplitude distribution was generated and its results were compared with the Nakagami-m and Rice models.
- The performance of 6 GPS receivers under scintillation environment was studied.
- An ionospheric prediction model was developed in collaboration with Dr. Emanoei Costa from PUC/Rio de Janeiro. Data from one VHF radar and from GPS receiver was used.
- The correlation of the equatorial S4 scintillation index and S4 under EIA was analyzed.

15. SUBJECT TERMS
- Ionospheric plumes characterization at 3 longitudinal sectors;
- Scintillation prediction

16. SECURITY CLASSIFICATION OF:
Unclassified

17. LIMITATION OF ABSTRACT
UU

18. NUMBER OF PAGES
01

19a. NAME OF RESPONSIBLE PERSON
Eurico R. de Paula

19b. TELEPHONE NUMBER (include area code)
55-12-32087163

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. 239.18
Final Report
Ionospheric Irregularities Predictions and Plumes Characterization for Satellite Data Validation and Calibration

Eurico R. de Paula¹, F.S. Fabiano², E.A. Kherani¹, R.Y.C. Cueva¹,³

1 - National Institute for Space Research-INPE  Brazil
2- University of Texas at Dallas – UTD
3 – CRAAM – Mackenzie – São Paulo

June 19, 2013
Outline

• Plume characterization
• GPS signal analysis
• Ionospheric scintillation using GPS and VHF radar
• Irregularity prediction model (Emanoel Costa)
• Irregularity prediction
• 6 different GNSS receivers campaign
• References
São Luís, Jicamarca and Christmas Island plumes characterization in function of solar flux

The following plume parameters were analyzed for São Luís, Jicamarca and Christmas Island:

- $H_i$ – Bottom type onset altitude
- $H_p$ – Plume onset altitude
- $H_{pk}$ – Peak plume altitude
- $T_i$ – UT Time for $H_i$
- $T_p$ – UT Time for $H_p$
Onset altitude of bottom-type, plume and plume peak increase almost linearly with increasing solar flux. Onset time decrease with solar flux.
Onset altitude of bottom-type, plume and plume peak increase almost linearly with increasing solar flux. Onset time presents almost no variation with solar flux.
Plumes characterization in function of solar flux

Bottom-type, plume onset and peak altitude variation with solar flux for the 3 stations

Bottom-type and plume onset altitude present similar behavior for the 3 stations, while the plume altitude peak presents smaller inclination for Christmas Island.
Plumes characterization in function of solar flux

Bottom-Type and plume onset time with solar flux for the 3 stations

Bottom-type and plume onset time presents similar behavior for São Luís and Jicamarca however larger variation (onset time earlier for higher solar fluxes) for Christmas Island.
Plumes characterization

Ionospheric irregularity zonal velocity calculation using VHF radar interferometry (in collaboration with Fabiano Rodrigues from UTD)

São Luís VHF radar antenna sets experimental setup

- Today: Single baseline observations
## Plumes characterization

### São Luís VHF radar experimental setup

<table>
<thead>
<tr>
<th></th>
<th>150-km echoes*</th>
<th>F-region*</th>
</tr>
</thead>
<tbody>
<tr>
<td>TX power</td>
<td>4 kW</td>
<td>2x4 kW</td>
</tr>
<tr>
<td>Code length</td>
<td>28 bauds</td>
<td>28 bauds</td>
</tr>
<tr>
<td>Baud length</td>
<td>1 km</td>
<td>2.5 km</td>
</tr>
<tr>
<td>IPP</td>
<td>600 km</td>
<td>1,400 km</td>
</tr>
<tr>
<td>Initial sampling height</td>
<td>90 km</td>
<td>200 km</td>
</tr>
<tr>
<td>Max sampling height</td>
<td>210 km</td>
<td>875 km</td>
</tr>
<tr>
<td>Doppler velocities</td>
<td>± 40 m/s</td>
<td>± 268 m/s</td>
</tr>
</tbody>
</table>

*Typical configuration
Plumes characterization

Results

03-Dec-2010

SNR

Vertical

Zonal

07-Dec-2010

SNR

Vertical

Zonal
Plumes characterization

Results

Relatively small height variation

03-Dec-2010
Plumes caracterization

Results

Slower drifts at lowest heights.

07-Dec-2010
Conclusions for zonal drift calculations

- Results confirm the possibility of estimating relative zonal velocities.
  - Regions of westward drifts (bottomside F-region).
  - Determination of the height of the shear node (as high as 450 km).

- The turbulent nature of ESF, however, makes it less than straightforward to accurately determine the absolute mean bulk flow.

- Future work includes:
  - Long-term (several minutes) tracking of irregularity clusters to derive mean zonal drifts.
  - More comprehensive comparison, if possible, with plasma bubble velocities and winds.
GPS signal analysis

S₄ occurrences (in collaboration with Dr. Alison Moraes from IAE/CTA)

Distribution of the S₄ indices of the observations available between Dec 14th 2001 and Jan 14th 2002, as a function of local time.
GPS signal analysis

Decorrelation time

The autocorrelation function of the normalized signal amplitude scintillation is given by

\[ A_R(\tau) = \frac{E[(R(t) - \bar{z})(R(t + \tau) - \bar{z})]}{\sigma_R^2} \]

The \( \tau_0 \) value is defined as the time lag at which the autocorrelation function falls off by \( e^{-1} \) from its maximum (zero lag) value:

\[ \frac{A_R(\tau_0)}{A_R(0)} = \exp(-1) \]

While the \( S_4 \) index is an indicator of the depth (or magnitude) of amplitude fadings, the decorrelation time \( (\tau_0) \) is an indicator of rapidity of the fadings.
The variability of amplitude scintillation patterns

Examples illustrating the variability in the decorrelation time made during the campaign of observations used in this study. In all cases the time series of measured signal amplitude have approximately the same $S_4$ ($\sim 0.9$), but very distinct $\tau_0$ values.
GPS signal analysis
Example of observations

Sao Jose dos Campos on December 14th, 2001. Panel (a) C/N0 of the L1 signal received from satellite PRN 28. (b) S4 index. (c) azimuth and elevation angle of the PRN 28. (d) decorrelation time ($\tau_0$) (is not computed for S4<0.1). This example illustrates that the scintillation intensity decreases and the decorrelation time increases as time progresses.
GPS signal analysis

$S_4$ vs $\tau_0$

- Linear relationship between $S_4$ and $\tau_0$;
- Variability/spread of $\tau_0$ values as well as the mean value of $\tau_0$ tend to decrease as scintillation intensity ($S_4$) increases.
- Decorrelation times decreases as scintillation becomes stronger, and vice versa.
• $\alpha$-$\mu$ distribution (Yacoub, 2007). This model assumes the signal as a composition of many clusters of multipath waves instead of just one. The result of such an assumption is a more comprehensive characterization of electromagnetic scattering phenomena.
• Our results show that the Nakagami-m PDF performed better than the Rice PDF.
• $\alpha$-$\mu$ distribution, however, outperformed the Nakagami-m and Rice PDFs for all cases.
Ionospheric scintillation using GPS over South America

LISN GPS Network & 3 more Networks

LISN GPS Network (in green) & 3 more Networks (in red). The gray arrows indicate the Jicamarca and São Luís digisondes, the diamond indicate the position of the imager at São João do Cariri.
Ionospheric scintillation using GPS over South America

Seasonal percentage of scintillation occurrence for 3 stations

Black histogram: Observed plumes and white histogram: Spread F. At São Luís plume occurrence is from September to March with a peak at summer. At Jicamarca the peaks are at equinoxes and for Christmas Island is on August. The difference between black and white bars represent bottom-type structures.
• Radio waves passing through the irregularities diffract producing signal fading and strong scintillations even at L frequencies.
• The contribution in the model was made in mapping the irregularities along the magnetic field lines.
We are using zonal drift velocity from climatological model (Arruda et al., 2006). \( V = 150 \text{m/s} \) between 19-23 UT, 80 m/s between 23-29 UT.
Irregularity prediction model (Emanoel Costa/Ricardo Yvan)

\[ \sqrt{\langle \Delta N^2 \rangle} \approx \frac{2\pi}{r_e} \sqrt{\frac{k_B T_{\text{sky}} B_N L_{\text{tot}}}{G^2 g^2 \theta_{3\perp} \delta h_{\tau} (\lambda_r/2)^3 P}} \pi S_1 L_o^{p-2} L_b^{q-1} \frac{(\lambda_r/2)^q}{(\lambda_r/2)^q} \]

\[ r \sqrt{\frac{s}{n}} \approx Cte_{\text{Radar}} \cdot r \sqrt{\frac{s}{n}} \]

### Power Spectral Parameters

- \( \langle \Delta N^2 \rangle \): Mean Square Electron Density
- \( S/N \): Signal to Noise ratio

Obtained from C/NOFS satellite for 2008

### Radar Parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>( L_o [km] )</td>
<td>12.500</td>
</tr>
<tr>
<td>( L_b [km] )</td>
<td>0.080</td>
</tr>
<tr>
<td>( p )</td>
<td>2.600</td>
</tr>
<tr>
<td>( q )</td>
<td>4.600</td>
</tr>
<tr>
<td>( S_1 )</td>
<td>3.210</td>
</tr>
<tr>
<td>( Freq [MHz] )</td>
<td>29.795</td>
</tr>
<tr>
<td>( Pt [kW] )</td>
<td>4.000</td>
</tr>
<tr>
<td>( E_{ff} )</td>
<td>0.500</td>
</tr>
<tr>
<td>( dh [km] )</td>
<td>2.500</td>
</tr>
<tr>
<td>( BW_{3dB} [deg])</td>
<td>10.000</td>
</tr>
<tr>
<td>( Gain [dB] )</td>
<td>26.000</td>
</tr>
<tr>
<td>( N_{Fig} [dB])</td>
<td>5.000</td>
</tr>
<tr>
<td>( T_{sys} [K] )</td>
<td>917.061</td>
</tr>
<tr>
<td>( T_{sky} [K]  )</td>
<td>10000.000</td>
</tr>
<tr>
<td>( BW [kHz] )</td>
<td>120.000</td>
</tr>
</tbody>
</table>
Irregularity prediction model (Emanoel Costa/Ricardo Yvan)

S4 (measured x calculated) for PRN 11 and 20 16 Nov. 2001
Irregularity prediction
Ionospheric irregularity precursors (prediction tentative)
Influence of MSTIDs and GWs on the irregularity generation (Ricardo’s PhD)

Wave oscillations of about 30 minutes were observed which give evidence of gravity waves (GW)
Irregularity prediction (Precursor)

Irregular base layer dynamics before the bubble triggering using radar imaging
(in collaboration with Alam Kherani from INPE)

Irregularity initiation in the base layer probably generated by the Rayleigh-Taylor and shear instabilities

With time this layer grows upward outside the shear region and becomes a bubble.

The bubble can grow in altitude, detached from the base layer.
Irregularity prediction (Precursor)

Irregular F and E layers dynamics before the bubble occurrence using VHF Radar

The Doppler velocity inside the irregular F layer shows wavy behavior. Similar behavior was observed in the irregular E layer with a time shift prior to the F layer. And this E layer behavior could be considered as a precursor of the bubble.
Irregularity prediction

The following procedures can also be used to predict irregularities:

• Ionosonde vertical drift calculations to establish thresholds to trigger irregularities (this work is being developed).
• Bubble velocity is eastward (during quiet period) so spaced GPS receivers / VHF receivers in the zonal direction (SCINDA) can be employed to predict bubble occurrence to eastward station.
6 different GNSS receivers campaign

To analyze their behavior under scintillation conditions (Septentrio, Novatel 4004B and GPS-Station6, ASTRA, GEC-PLESSEY Card – Cornell, Stanford - U Box) Keith Groves, Cesar Valladares, Todd Walter, Geoff Crowley, Paul Kintner†
Campaing of 6 different GNSS receivers (Stanford)
6 different GNSS receivers campaign
Different GNSS receivers behavior under scintillation conditions during March 24 2013 at São José dos Campos, São Paulo - Brazil

Good S4 agreement for the 6 receivers and for moderate scintillations – no strong scintillations tested
References

• Cueva, R.Y.C.; C. E. Valladares; E.R. de Paula; M. A. Abdu; I. Paulino; I.S. Batista; H. Takahashi (2012), Longitudinal and day-to-day variations of equatorial spread F occurrence from recent observations over South America, Submitted to Journal of Atmospheric and Solar-Terrestrial Physics.
• Kherani, E.A, E.R de Paula, M.A. Abdu, Simultaneous wave-like Doppler modulations within the irregular bottom-type/bottomside F layer and irregular E layer prior to the F region plume, to be submitted to J.G.R.
• Rodrigues, F.S., de Paula, E.R., Interferometric radar observations of F- region irregularities in Brazil, AGU Meeting of the Americas, Cancun, Mexico, 14-17, 2013.