First Results of Ionospheric Tomography using the LISN Network

ELECTRICAL & COMPUTER ENGINEERING

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Abstract

The Low-Latitude Ionospheric Sensor Network (LISN) is a distributed observatory located in South America. Composed of 50 dual frequency GPS receivers, this facility's measurements can be used to compute Total Electron Content (TEC), especially the enhancements that occur near midnight.

Taking advantage of the large number of stations of this network, Computerized Tomography (CT) is used to study the electron density distribution of the low-latitude ionosphere, especially in the moments of sudden increases in TEC between sunset until past local midnight. An iterative method, namely the multiplicative algebraic reconstruction technique (MART) is evaluated. Results show advantages and disadvantages. While iterative methods show satisfactory results for specific initial conditions, they do very poorly in other cases. This is in contrast to inverse methods that perform well without the help of any initial guesses. Iterative methods are also limited to the number of ray paths for determining the resolution of the image. An advantage of LISN is that it collects data approximately every 30 seconds, which can be considered low latency for tomography purposes.

TEC - Definition and Estimation

TEC is the number of free electrons along the path between two points (satellite - receiver). Mathematically, it can be represented as:

$$\text{TEC} = \int_p n_e(s)ds$$

In 2006, Milla [1] detailed how to estimate absolute TEC from the RINEX files deposited in LISN. Every station from this network is able to measure and store the pseudorange P and carrier phase Φ data from a satellite's modulated signal. P does not represent the true geometric range because instrumental and propagation delays affect the measurement. On the other hand, Φ is the total number of full carrier cycles plus a cycle fraction between transmission and reception of the GPS signals, and multiplied by the carrier wavelength. Although this measurement is less noisy than P, LISN only saves the fraction of the cycle while the total cycle number remains unknown, causing an ambiguity in the TEC.

Pseudorange (P):

$$P_i = \rho + c(dt^r - dt^s) + \Delta_i^{ion} + \Delta_i^{trop} + B_i^r + B_i^s + m_i^P + n_i^P$$

Carrier Phase (Φ):

$$\Phi_i\lambda_i = \rho + c(dt^r - dt^s) + N_i\lambda_i - \Delta_i^{ion} + \Delta_i^{trop} + B_i^r + B_i^s + m_i^\phi + n_i^\phi$$

TEC estimation from P and Φ:

$$\text{TEC}_P = 9.52(P_2 - P_1) + \Delta B^r + \Delta B^s + \Delta m^P + \Delta n^P$$

$$\text{TEC}_\Phi = 9.52(\Phi_1\lambda_1 - \Phi_2\lambda_2) - (N_1\lambda_1 - N_2\lambda_2) + \Delta B^r + \Delta B^s + \Delta m^\Phi + \Delta n^\Phi$$

Absolute TEC estimation:

$$\text{TEC}_{\Phi P} = \text{TEC}_\Phi - \langle \text{TEC}_\Phi - \text{TEC}_P \rangle$$

$$\text{TEC} \approx \text{TEC}_{\Phi P} - \Delta B^s - \Delta B^r$$

2D Tomography Reconstruction

On January 17, 2011 a Equatorial Spread F (ESF) was detected by the JULIA radar located at the Jicamarca Radio Observatory. The scattered signal appears between 1:30 UT and 3:00 UT (7:30 pm and 9:00 pm local time). This event was detected in LISN GPS stations located at or near longitude 74°W (Bogota, Pucallpa, Huancayo, and Ayacucho). The TEC measured in these stations experienced a variation during the time of the event. A GPS satellite (PRN 22) orbited around 74°W longitude that day. This facilitates a 2D latitude-altitude tomography reconstruction.

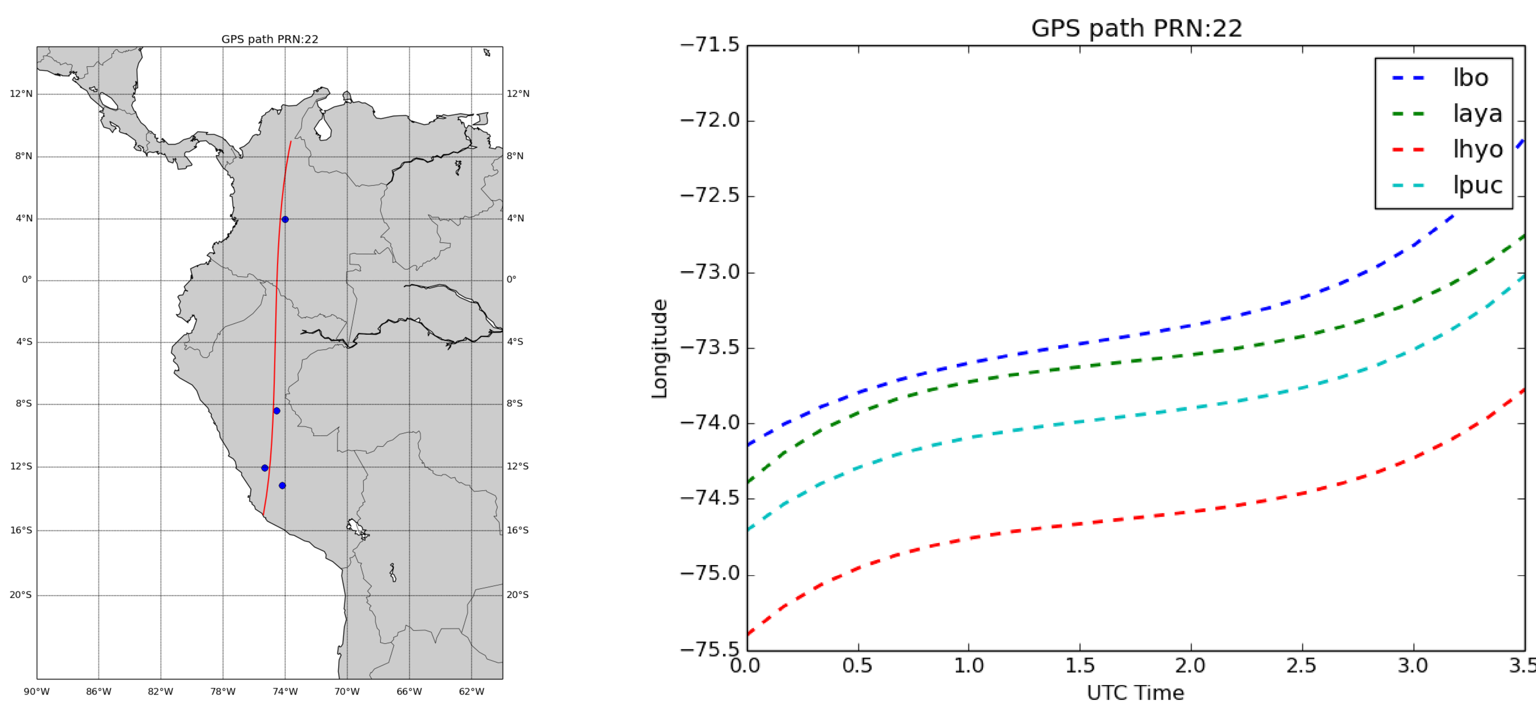

Fig. 1: Left. South America map with LISN stations and GPS Satellite (PRN 22) path on January 17, 2011. Right. GPS Satellite (PRN 22) trajectory on January 17, 2011 between 00:00 and 03:30 hours UTC as seen by four LISN receivers.

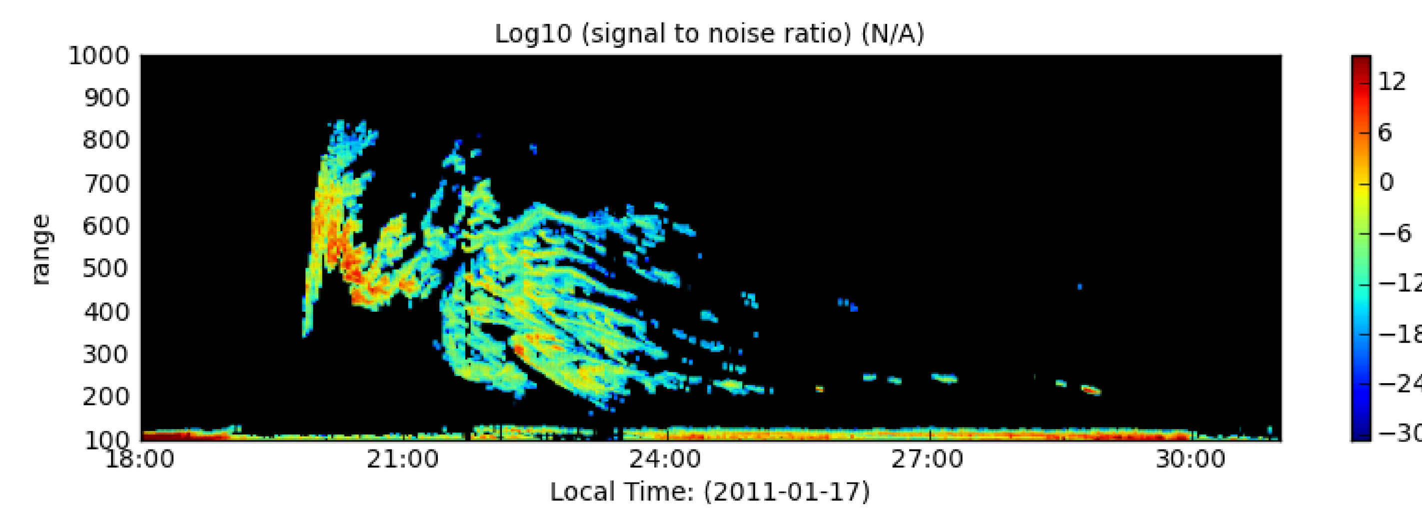

Fig. 2: ESF event viewed by the JULIA radar on January 17, 2011.

Multiplicative Algebraic Reconstruction Technique

Ionospheric tomography, a concept which was first proposed by Austen et al. [2], is an inversion technique for reconstructing the ionospheric density distribution from TEC measurements made by multiple receivers.

$$y_i = \sum_{j=1}^{N} A_{ij}x_j + e_i; \quad i = 1, 2, ..., M$$

MART is an entropy-optimization algorithm based on the following nonlinear iteration:

$$\mathbf{x^{k+1}} = \mathbf{x^k}\left(\frac{\mathbf{y_i}}{\sum_{j=1}^{N_b} \mathbf{a_{ij}\, x_j^k}}\right)^{\lambda_k a_{ij}/a_{max}} \qquad \text{where,}$$

x^{k+1} is the electron density from iteration $k+1$,
λ is a relaxation parameter, usually between $\langle 0, 1 \rangle$, and
$\sum_{j=1}^{N_b} a_{ij}\, x_j^k$ is a scan through each cell from the ionosphere grid.

After many iterations the result converges to a solution. An initial guess x^0 is taken from the International Reference Ionosphere (IRI).

Results

A MART algorithm was used to construct a 2D Electron Density Map. Error was minimized after 45 iterations. Some irregularities are observed in the structures.

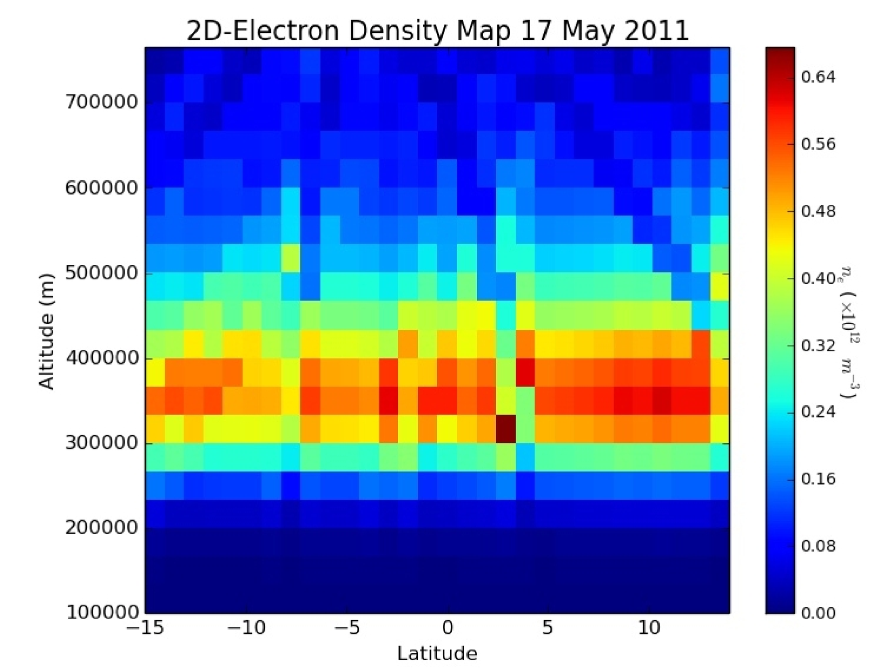

Fig. 3: 2D Electron Density Map generated after 30 MART iterations between GPS Satellite (PRN 22) and four receivers located around 74°W on January 17, 2011.

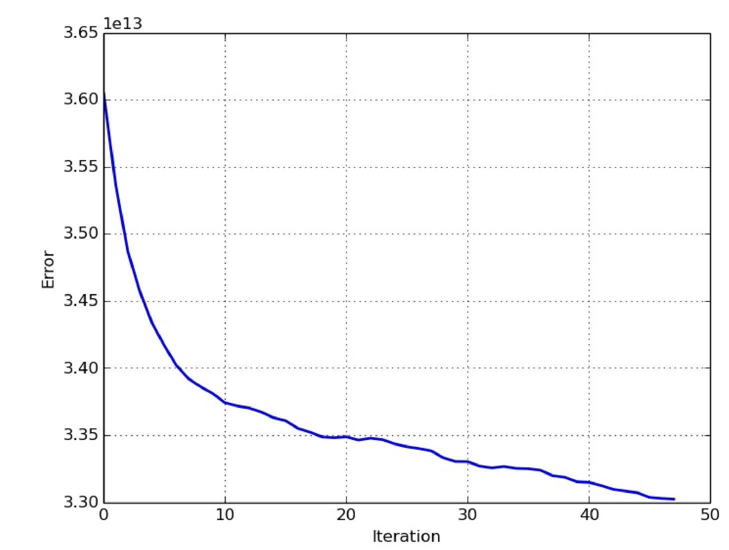

Fig. 4: Error computed after every MART iteration

Conclusion and Future Work

We have explored the potential of LISN as a distributed observatory, composed of nearly 50 GPS receivers and able to measure delays of 32 GPS satellites at the same time in every station. Extending this work to 3D tomography is a challenge, but it should allow us to measure or infer the state of the F- and E-region at the foot of the field tubes that go unstable [3].

SAMI2 or SAMI3 ionosphere models may be used as a reference to determine the initial guess, and to determine the confidence of the results obtained.

More sophisticated inverse methods can be applied in order to refine the tomography reconstruction. One advantage of MART is that it works only with positive unknowns which is the case for Electron density data.

References

[1] Marco A. Milla. *Calculating TECs using GPS data from South America.* 2006.

[2] Jeffrey R Austen, Steven J Franke, and CH Liu. "Ionospheric imaging using computerized tomography". In: *Radio Science* 23.3 (1988), pp. 299–307.

[3] RF Woodman. "Spread F–an old equatorial aeronomy problem finally resolved?" In: *Annales Geophysicae.* Vol. 27. 5. Copernicus GmbH. 2009, pp. 1915–1934.