Time-dependent tomographic hydrogen density estimation and its role in the ring current decay after storm-time

Gonzalo Cucho-Padin, Lara Waldrop

University of Illinois at Urbana Champaing, Urbana, IL e-mail: gac3@illinois.edu

Introduction

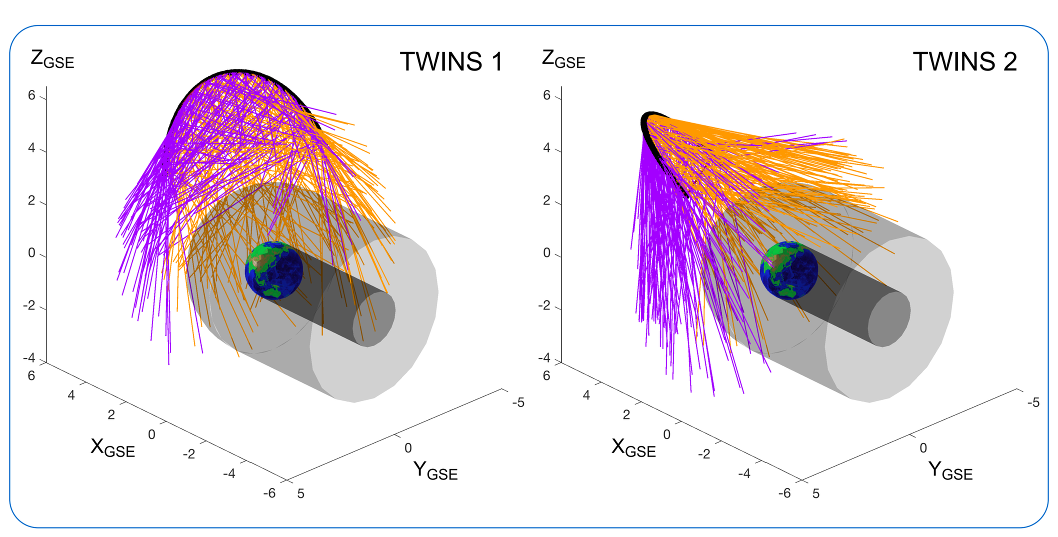
- Ring current (RC) decay following a magnetic storm is driven by charge exchange collisions with cold exospheric neutral hydrogen (H) atoms, forming energetic neutral atoms (ENAs) which can escape the Earth system. Knowledge of the global, 3D distribution of exospheric H is required for accurate interpretation of ENA flux measurements and RC modeling.
- Hydrogen atoms (H) in Earth's upper exosphere resonantly scatter solar Lyman-alpha (121.567 nm) radiation, creating the ultraviolet optical signature known as the H geocorona.
- In the **optically thin** region, located beyond ~3R_E, the density number of H atoms is relatively low, such scattering events can be assumed to occur exactly once.
- The relationship between optically thin emission radiance (I) and the exospheric H density (n_H) along the line of sight is given by:

$$I(\mathbf{r},\hat{\mathbf{n}},t) = \frac{g^*}{10^6}\int_0^{L_{max}} n_H(l,t)\Psi(\beta)dl + I_{IP}(\hat{\mathbf{r}},\hat{\mathbf{n}},t)$$

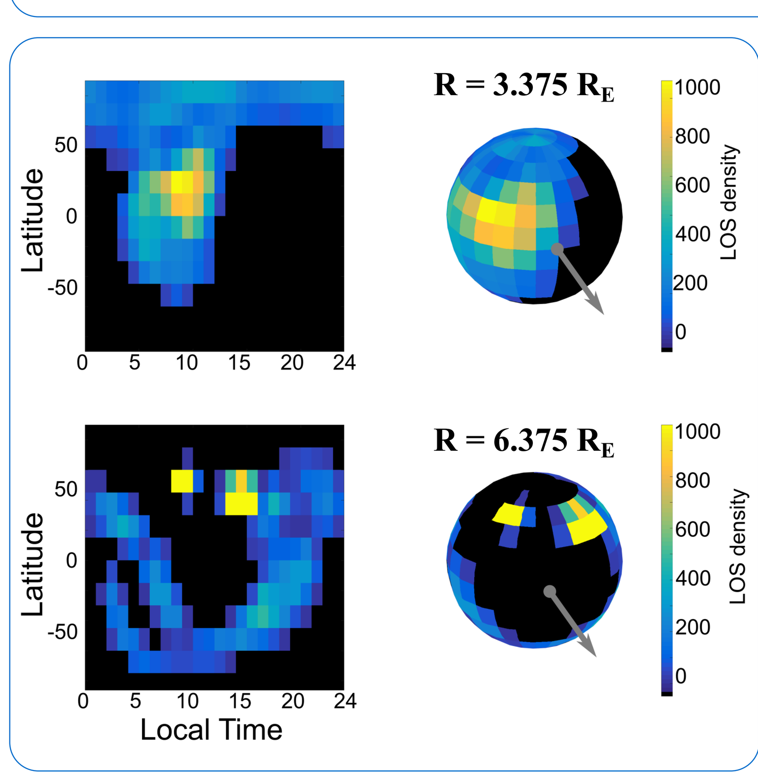
- Previous methods that estimate the 3D hydrogen density distributions have been based on **parametric fitting** of assumed functional forms involving spherical harmonics expansions.
- The linearity of previous equation allows for non-parametric formulation of H estimation as a tomographic inverse problem that can be solved through regularization techniques. This approach was evaluated with synthetic and real data in our previous work [3].
- Here, we use this approach to investigate the 3D, time-dependent structure of the outer exosphere during a geomagnetic storm that occurred on 15 June 2008, essentially in the ring current region [3-6] R_E.

Data

- **TWINS mission:** Comprised of two (2) satellites which enable stereoscopic sensing of the magnetosphere. Each satellite has two (2) Lyman-alpha detectors (LADs) that acquired Ly-alpha (121.6 nm) scattered emission from neutral hydrogen. The data used in this study is from June 14, 15 and 16 of 2013 where a -39 nT geomagnetic storm ocurred.



Orbits (in black line) for both TWINS1/2. Line-of-sight LOS from LAD1 in orange and LAD2 in purple. Earth's shadow zone modeled as a cylinder.

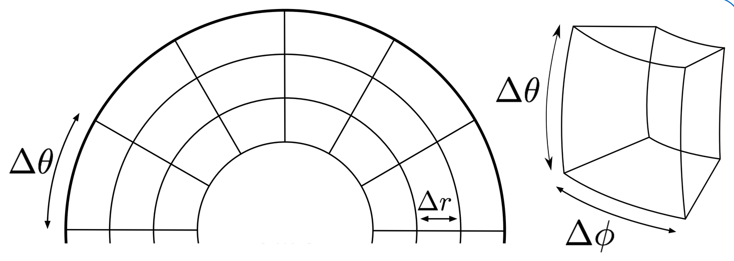


Example of LOS density profile for two radii. These plots are for the total LOSs for both LAD1/2 in TWINS1 for the period 5am-9am on June 15, 2008

Methodology: Tomographic approach

Setting up the geometry

(1) Discretize region into J spherical voxels.
(2) Project unknown density function onto J orthonormal basis functions.
(3) Rewrite i^{th} measurement of intensity and cast measurement ensemble as a matrix equation.



$$y_i(\mathbf{r}_i,\hat{\mathbf{n}}_i) = \frac{g^*(\mathbf{r}_i)}{10^6}\int_0^{L_{max}[\hat{\mathbf{n}}_i]} n_H(\mathbf{r}')\Psi(\hat{\mathbf{n}}_i)dl$$

$$n_H(\mathbf{r}') = \sum_{j=1}^{N} x_j\delta_{H_j}(\mathbf{r}')$$

$$\mathbf{y} = L\mathbf{x}$$

$N_r = 12$, $N_\phi = 24$, $N_\theta = 24$

Inverse problem and regularization

Since the observation matrix L is not full rank, a regularization technique must be used to solve the system. We have selected the technique known as Robust, regularized, positive estimation (RRPE), defined as follows:

$$\hat{\mathbf{x}} = \arg\min_{\mathbf{x}\geq 0}\Phi(\mathbf{x})$$

$$\Phi(\mathbf{x}) = ||L\mathbf{x}-\mathbf{y}||_2^2 + \lambda RRPE(\mathbf{x})$$

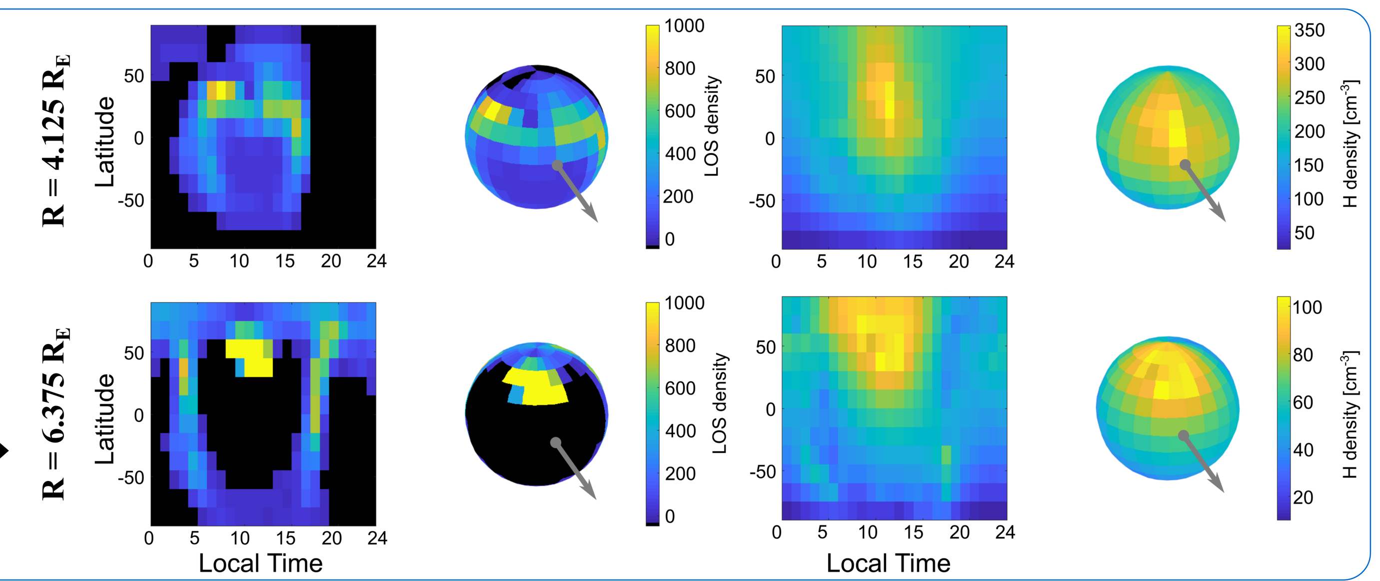
$$\lambda RRPE(x) = \lambda_r||x||_{D_r} + \lambda_\phi||x||_{D_\phi} + \lambda_\theta||x||_{D_\theta}$$

Where: $D_r \rightarrow \partial^2/\partial r^2$, $D_\phi \rightarrow \partial/\partial\phi$, $D_\theta \rightarrow \partial/\partial\theta$

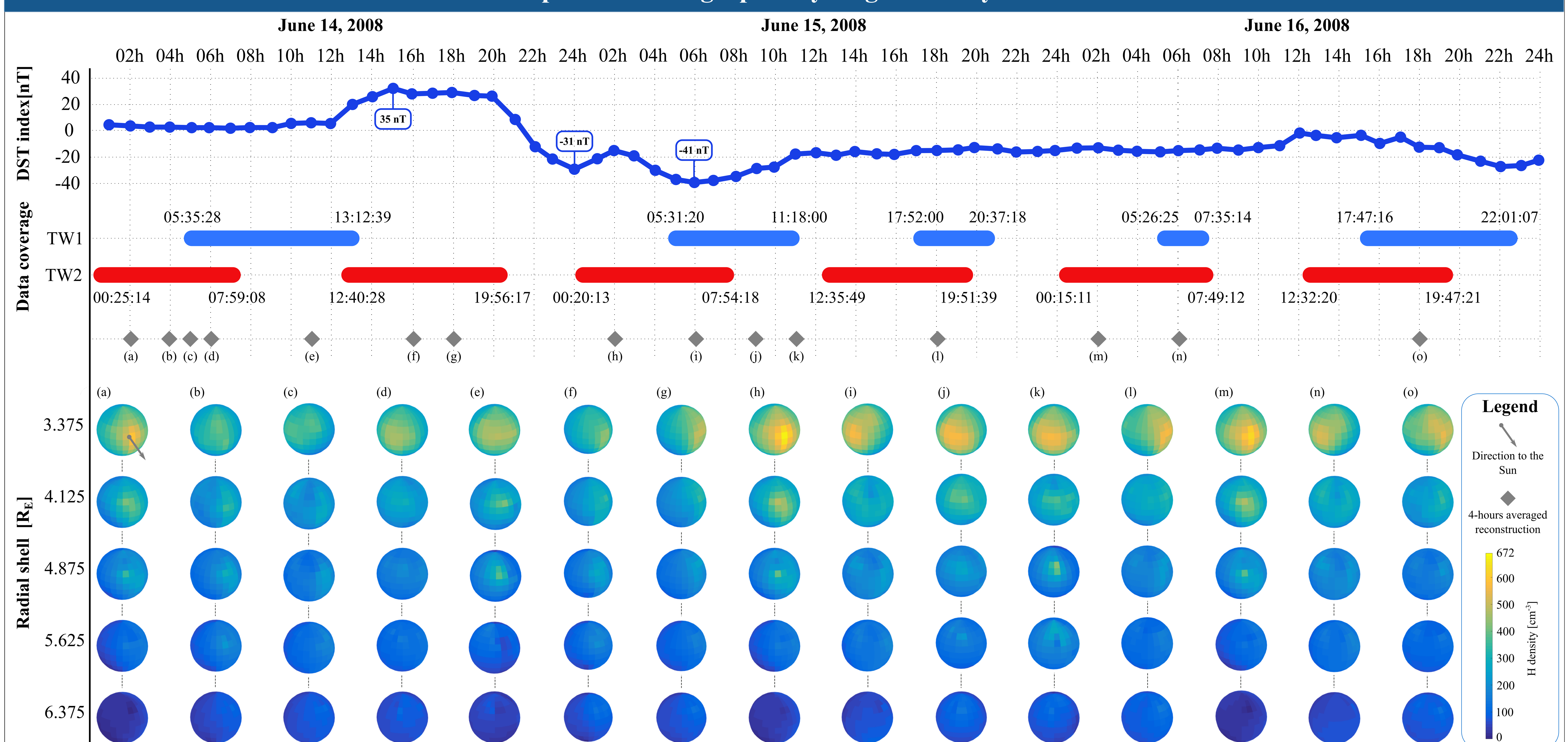
Previous results and main objective

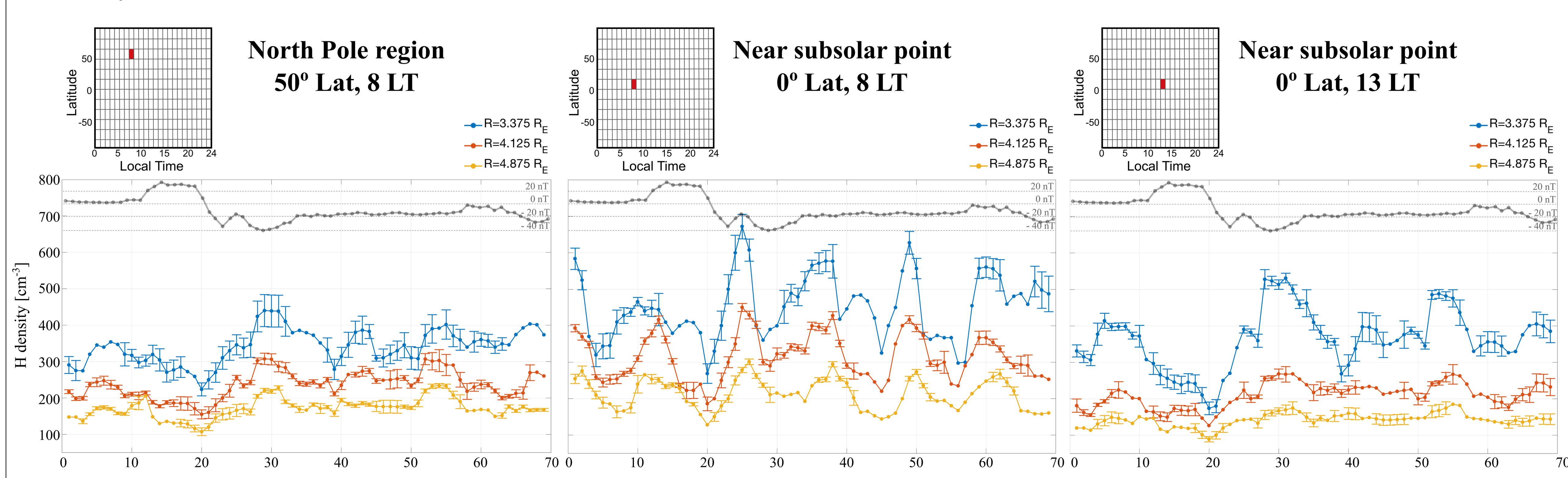
(1) Our previous work [3] demostrated the feasibility of the technique for exospheric atomic hydrogen estimation based on optically thin emission data from TWINS.
(2) We propose to analyze a storm-time event through the generation of **4-hours averaged** tomographic reconstruction and focus on the hydrogen structure in the RC region.

The 1-day averaged tomographic reconstruction from our previous work. The first column presents the line-of-sight LOS density per voxel for two different radii. The second column shows the reconstructed hydrogen densities for the same radial shells



Time-dependent tomographic hydrogen density estimation





Conclusions

- The 4-hour averaged tomographic reconstruction during June 15, 2008, show for the first time the exospheric hydrogen structure during the development of a geomagnetic storm.
- This study reveals a significant H density increment in the 3R_E region in response to the geomagnetic storm which could be related to transport processes in the lower atmospheric regions.
- Line-of-sight (LOS) coverage has a critical role in the tomographic reconstructions. Confidence in the estimated H densities is increased when a high number of LOS pass through a given voxel. Therefore, stereoscopic measurements (data acquired with both TWINS 1 and 2 during the same period of time) lead to the reduction of the uncertainty of the estimated H densities. However, these stereoscopic events ae infrequent.
- Future work will focus on the analysis of several geomagnetic storms in order to identify a more stable relationship between geomagnetic indicators such as DST , AP, KP and the estimated H density.

References

[1] Zoennchen et al. (2013), Exospheric hydrogen density for equinox and summer Atmospheric solstice observed with TWINS1/2 during solar minimun., *Annales Geophysicae, 31, 513-527.*

[2] Zoennchen et al. (2017), The response of the H geocorona between 3 and 8 Re to geomagnetic disturbances studied using TWINS stereo Lyman-alpha data, *Annales Geophysicae, 35, 171 - 179.*

[3] Cucho-Padin G. and Waldrop L. (2018), Tomographic estimation of exospheric hydrogen density distributions. *Journal of Geophysical Research: Space Physics, 123..*

Acknowledgment

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