Next Generation Methodologies to Advance Space Weather Monitoring and Predictability: A New Perspective through Network Analysis

McGranaghan et al. [2017]

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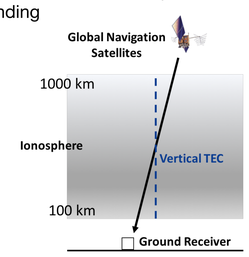
Key Findings

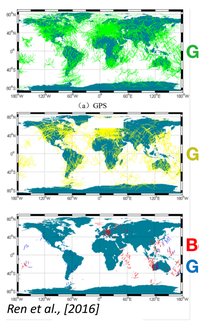
- First ever complex network theory based analysis of high-latitude total electron content (TEC) obtained from Global Navigation Satellite System (GNSS) signals
- Network analysis reveals significant structure in TEC correlation patterns and we discover that important characteristic scale sizes in TEC data vary across season and hemisphere
- Data-driven analyses illustrate importance of innovation at intersection of disciplines to the future of space weather research

Introduction

Global Navigation Satellite Systems (GNSS) are among the most important systems vulnerable to space weather, but are also one of the premier tools to facilitate new space weather understanding

Global monitoring of near-Earth space environment (geospace) not possible before GNSS signals





Ren et al., [2016]

Total electron content (TEC) data, inferred from GNSS signal delays during passage through the ionosphere, provide critical information about the Earth's ionosphere at higher cadence and over a larger portion of the globe than any other single data set

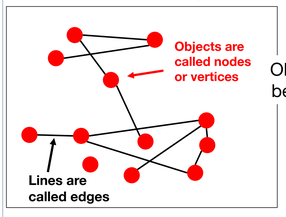
There is an opportunity for GNSS signals to be the foundation of the space weather observational system

However, characteristics of TEC data at high-latitudes are not well understood and novel, sophisticated approaches are needed to:

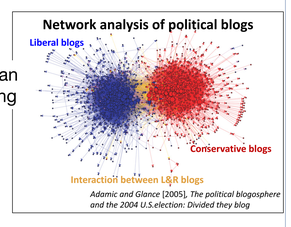
- Understand the information content of these data and
- Gain the most scientific utility from them

Network Analysis (NA) Technique

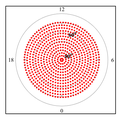
What is network analysis?



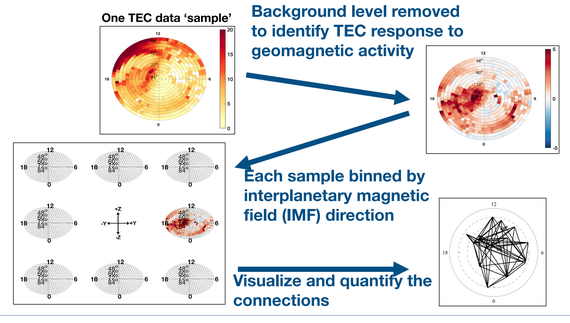
Objects can be anything



In geophysical applications, objects are grid points:



Application to high-latitude TEC:

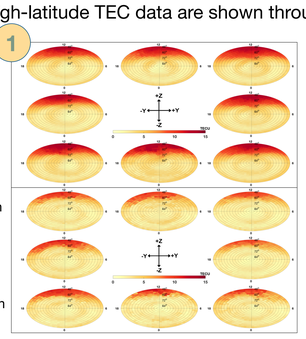


High-latitude, IMF–dependent network analysis results

We show results for the northern and southern hemispheres during local winter in 2016 (see *McGranaghan et al.*, [2017] for analysis of extended periods)

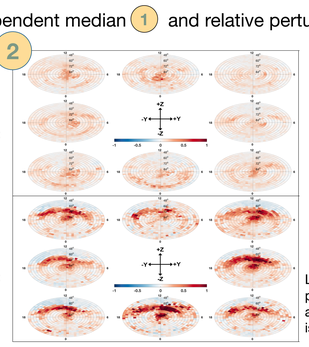
First, the characteristics of the high-latitude TEC data are shown through IMF-dependent median (1) and relative perturbation (2) figures

1



Local winter monthly median TEC distributions for northern (top) and southern (bottom) hemispheres. Data are TEC units (TECU, 1 TECU = 10^{16} el/m^2) in AACGM MLAT-MLT coordinates with 3° MLAT resolution and variable MLT resolution to yield equal area bins. Interplanetary magnetic field (IMF) clock angles increase in the clockwise direction in 45° increments.

2



Local winter average relative TEC perturbation distributions for northern (top) and southern (bottom) hemispheres. Format is the same as Figure 1.

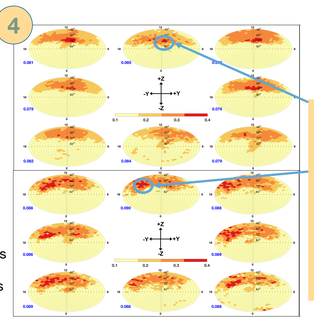
Relative perturbations are then used to calculate spatio-temporal correlations between each high-latitude (50-90°) grid point and networks are constructed (a connection occurs if the correlation between grid points exceeds a threshold). We use several robust mathematical measures to quantify and study network behavior. These measures are described (3) and visualized (4) - (6) below.

3

Network measures used to study network behavior

Measure	Significance (Interpretation)
Degree Centrality (4)	Influence of grid points on network function (larger = greater influence)
Median geodesic separation distance (5)	Scale sizes of connectivity (larger = longer range connections)
Local clustering coefficient (6)	Spatial continuity of TEC (larger = more spatially continuous)

4



Degree centrality distributions in same format as Figure 1. Global high-latitude averages are shown in blue text.

Cusp and ionospheric projection of magnetospheric boundary layers different between hemispheres

Different magnetosphere-ionosphere connection

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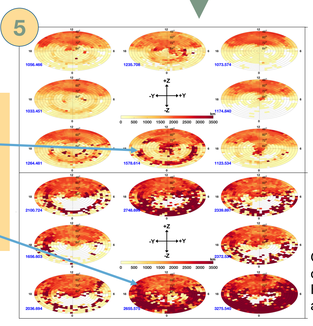
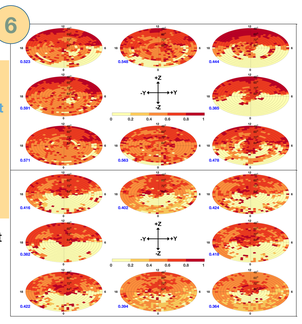


IMF dependency greater in northern hemisphere

Longer range connections in southern hemisphere

Geodesic separation distributions in same format as Figure 1. Global high-latitude averages are shown in blue text.

6



Larger local clustering coefficient implies northern hemisphere TEC correlations are more spatially continuous

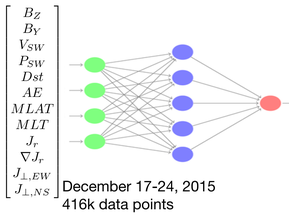
Local clustering coefficient distributions in same format as Figure 1. Global high-latitude averages are shown in blue text.

Enabling GNSS signal data to investigate complex geospace phenomena

TEC networks suggest GNSS data contain information about magnetosphere-ionosphere (MI) coupling

- Can GNSS signals be used to study/proxy complex phenomena in geospace?
- To what extent can relationships be exploited for space weather prediction?

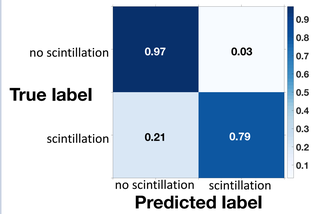
December 2015 case study to investigate techniques to discover relationships in geospace

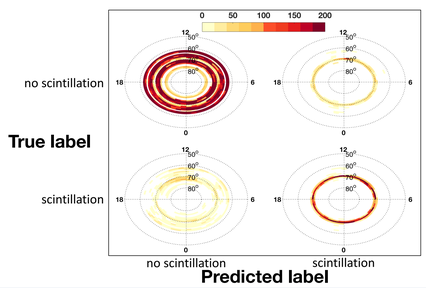


December 17-24, 2015
416k data points

Predict occurrence of GNSS signal phase scintillation (σ_ϕ)

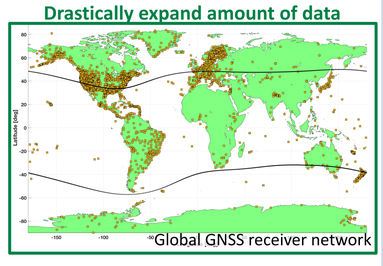
$\sigma_\phi >$ threshold = scintillation
$\sigma_\phi <$ threshold = no scintillation



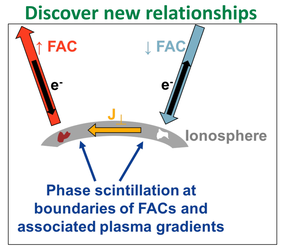


What's next?

Drastically expand amount of data



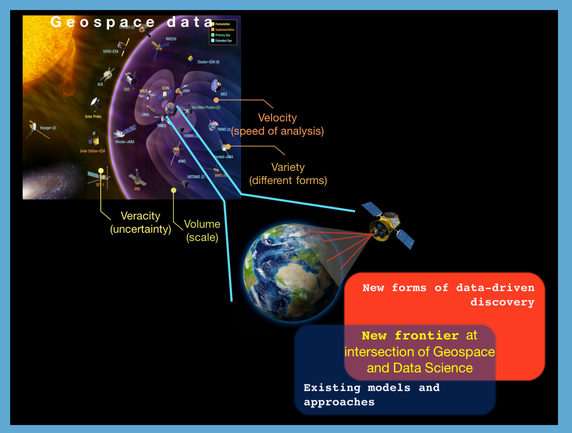
Discover new relationships



Significance: A 'new frontier'

'New frontier' in geospace sciences

- Built on **intersection** of data-driven discovery and existing approaches
- Increase utility of geospace observational system
- Focus on **relationships among data and actionable products** for space weather



Conclusions

Network analysis increased utility of information gleaned from GNSS signals:

NA reveals important new information about magnetosphere-ionosphere connections and space weather-related phenomena in TEC data

Network analysis and other data-driven approaches (e.g., machine learning) will enhance the efficiency of diverse space weather observational system:

Discover new relationships between diverse data sets

Illustrates broader importance of novel data-driven discovery to space weather:

'New frontier' of space weather research can be built on intersection of existing approaches and new data-driven discovery

References

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Acknowledgements

This research was supported by the NASA Living With a Star Jack Eddy Postdoctoral Fellowship Program, administered by the University Corporation for Atmospheric Research and coordinated through the Cooperative Programs for the Advancement of Earth System Science (CPAESS). Portions of this research were carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. We gratefully acknowledge the Massachusetts Institute of Technology (MIT) Atmospheric Sciences Group for providing the TEC data, which is publicly available from http://madrigal3.haystack.mit.edu/.