# Feasibility Study for Reconstructing the Spatial-Temporal Structure of TIDs from High-Resolution Backscatter Ionograms

**Dr. L. J. Nickisch, Dr. Sergey Fridman, Dr. Mark Hausman**

***NorthWest Research Associates, Monterey, California***

**Dr. Geoffrey S. San Antonio**

***Naval Research Laboratory, Radar Division***

**Presented at the 2015 Ionospheric Effects Symposium**

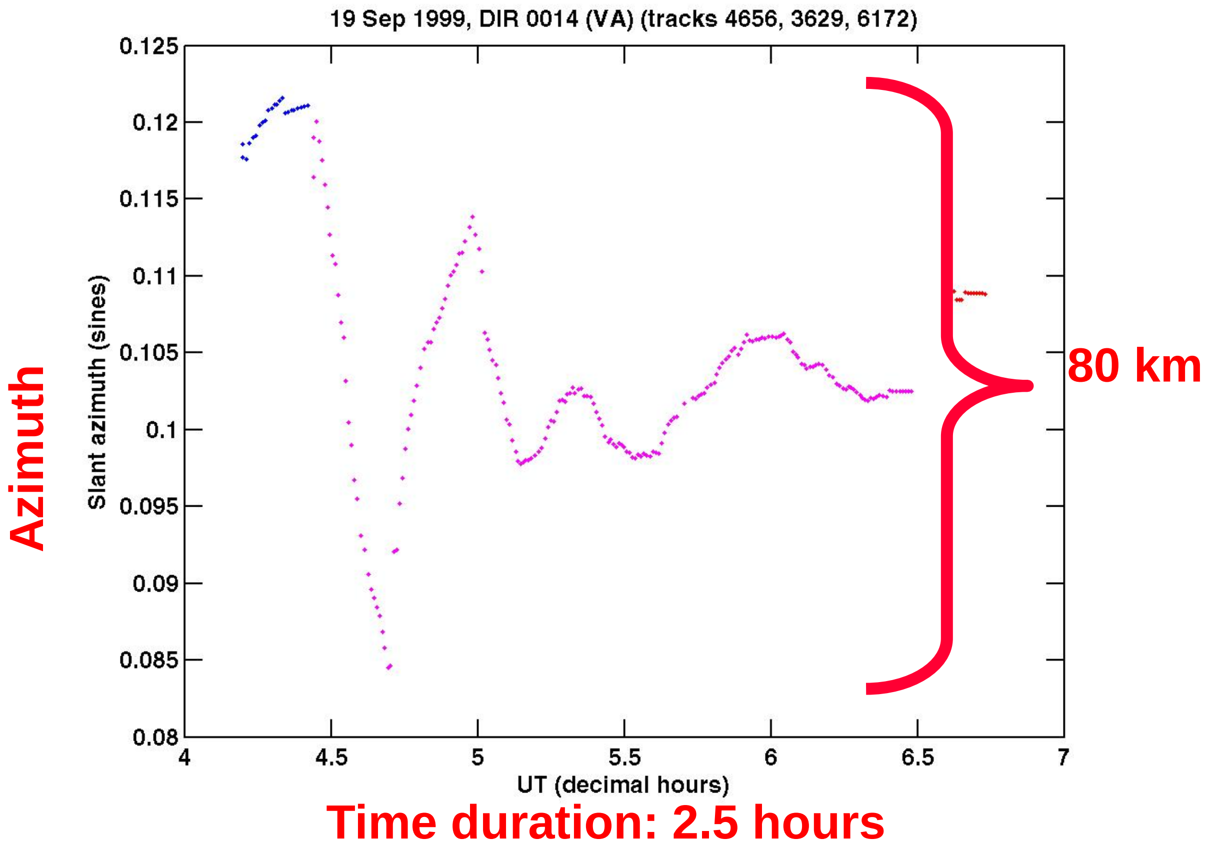
**12 May 2015**

NWRA
Since 1984

# Motivation

- **Medium-scale TIDs can cause large geolocation errors for over-the-horizon (OTH) radar**
  - **Apparent target location swings of tens of kilometers in 5-10 minutes**

- **ROTHR-Virginia return from stationary transponder in Jamaica**



NWRA
Since 1984

# Motivation (cont.)

- **OTH radars routinely collect backscatter soundings**
  - **Wide Sweep Backscatter Ionogram (WSBI)**
  - **Surface clutter returns as a function of delay and transmission frequency for a span of azimuths**
- **Can information from WSBIs be used to infer TID structure in real time?**

# GPS Ionospheric Inversion (GPSII)

- **The algorithm can assimilate diverse TEC-related data obtained on transionospheric propagation paths**
  - **GPS L1/L2 beacon signals ⇒ GPSII**
    - **Dual frequency group delay data (absolute TEC)**
    - **Dual frequency phase delay data (relative TEC)**
  - **TEC data obtained with LEO beacons**
  - **Occultation-type oblique TEC from space-based receivers (CHAMP, COSMIC, DORIS)**
- **Other data types**
  - **Vertical/Oblique soundings (especially important for HF skywave applications)**
  - **HF backscatter soundings**
  - **On-board plasma density measurements from satellites (such as CHAMP, DMSP)**
  - **Doppler sounding data**

# The Ionospheric Reconstruction Problem: Tikhonov Method

NWRA Since 1984

$$N(\mathbf{r},t) = N_0(\mathbf{r},t)e^{u(\mathbf{r},t)}$$
$$U = \{\{u(\mathbf{r},t)\}, \text{Biases}\}$$
$$Y \approx M[U]$$

*Y* is the set of measured absolute/relative TEC values and data points from other types of ionospheric measurements.

The solution must fit the data within errors of measurements. → $(Y - M[U])^T S^{-1}(Y - M[U]) / \dim(Y) \le 1$

**Error covariance matrix**

There are infinitely many such solutions:

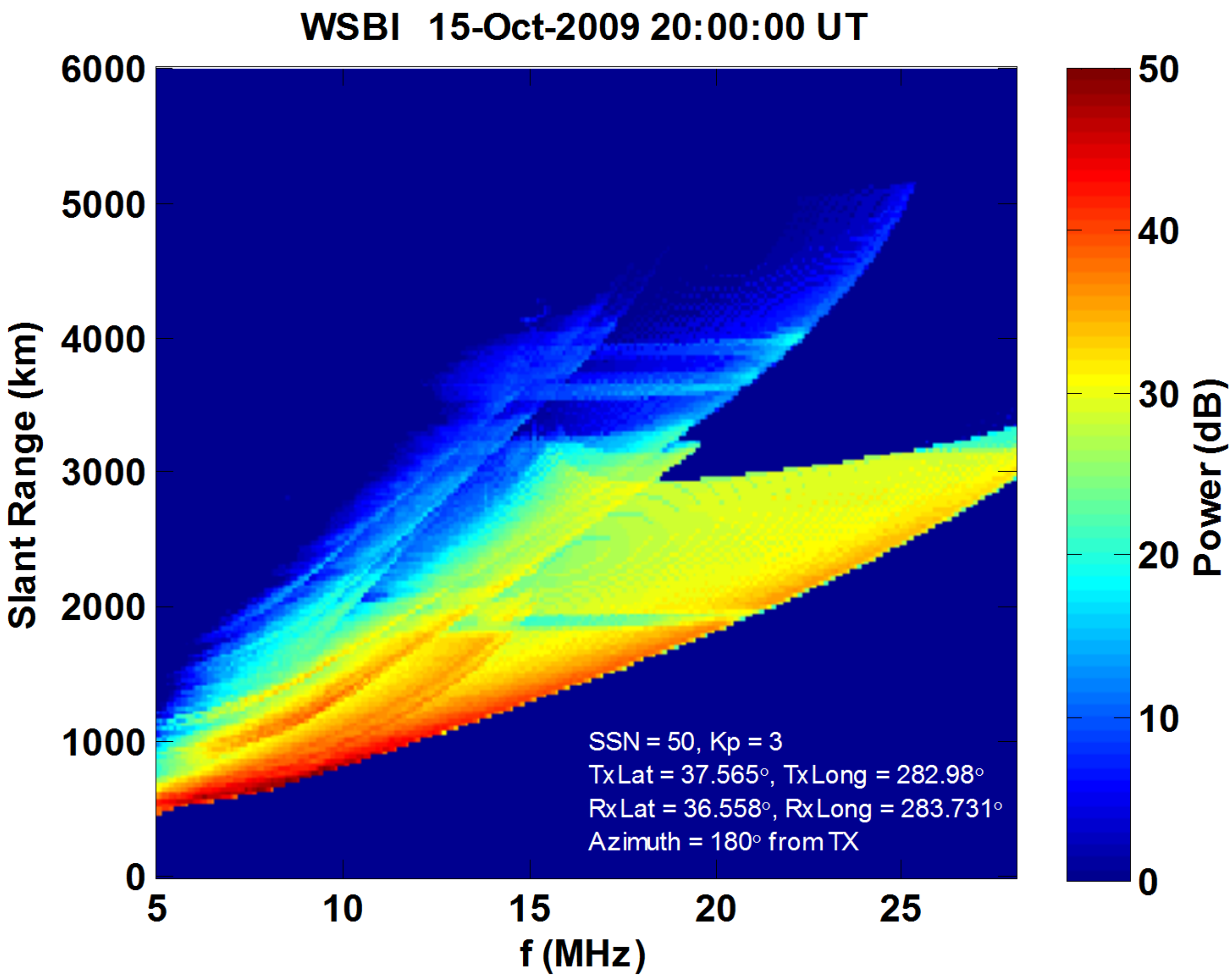
The smoothest solution is selected by minimizing the stabilizing functional → $U^T P^{-1} U \to \min$

**Pseudo-covariance matrix**

-The pseudo-covariance *P* matrix is defined in such a way that the stabilizing functional tends to take on larger values for unreasonably behaving solutions (“reasonable” ⇔ “smooth”).

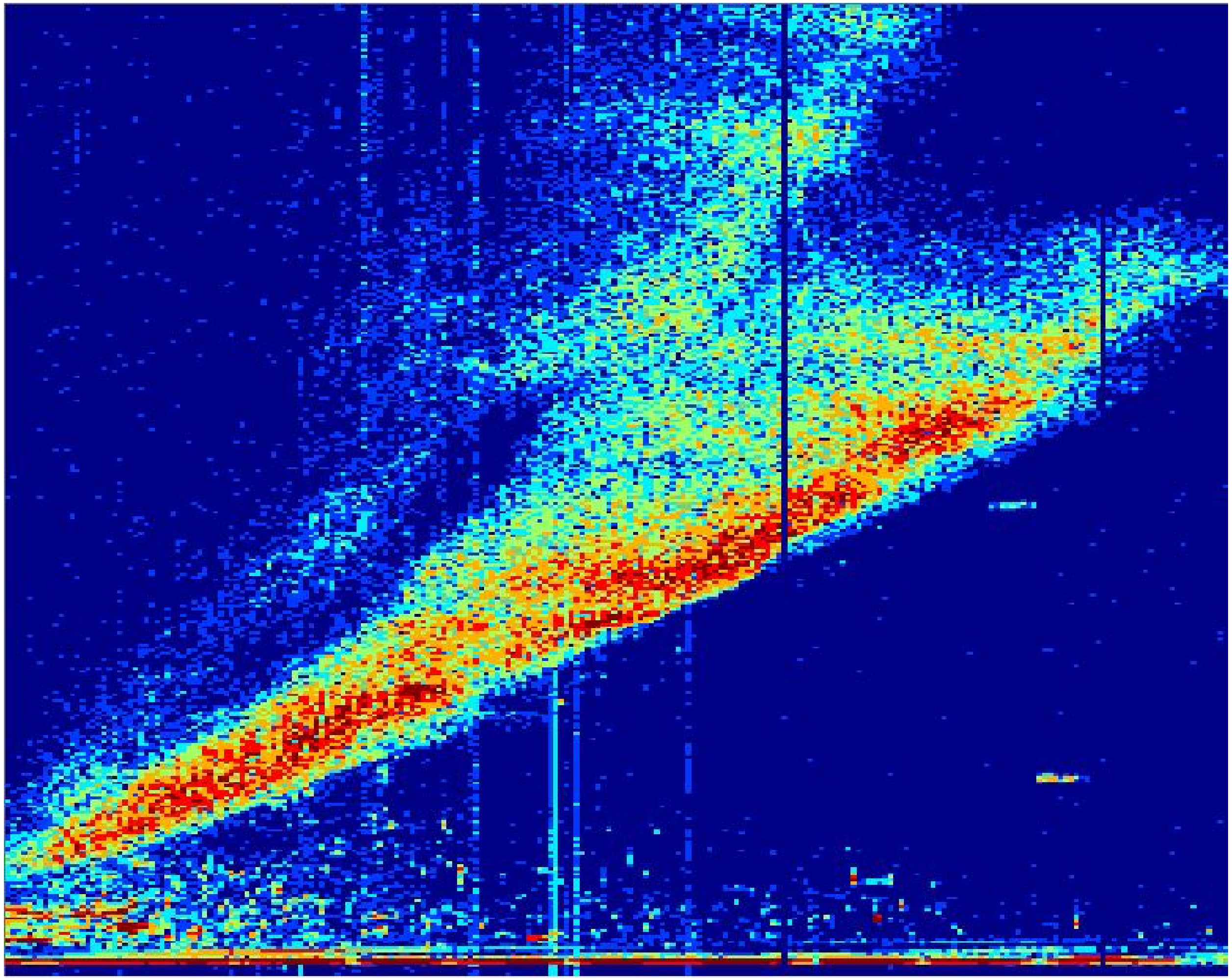
-The nonlinear optimization problem is solved iteratively (Newton-Kontorovich).

# Synthetic Wide-Sweep Backscatter Ionogram




**Generated by NWRA HiCIRF code**

# Real OTHR Backscatter Ionogram



**Encompasses ~10° azimuthal swath**

NWRA
Since 1984

# Can WSBI leading edge structure be assimilated to expose TIDs?

- ROTHR WSBIs are collected using only the end 28 elements of its 372 element receive array
  - Yields ~10° azimuthal resolution

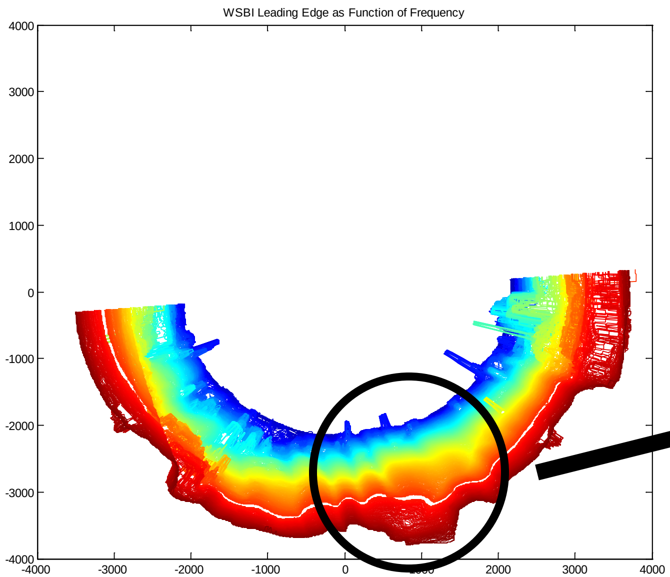
- Use of full aperture would allow WSBIs with ~1° spacing
  - Allows detection of leading edge TID structure

- Assimilating WSBI leading edge data would be an excellent way of mitigating TID effects on OTHR CR
  - WSBIs are routinely collected by OTHR
  - WSBIs densely sample the OTHR operational field of view
  - Modern digital technology will allow next generation OTHR to collect WSBIs using the full receive aperture without impacting the surveillance mission of the radar

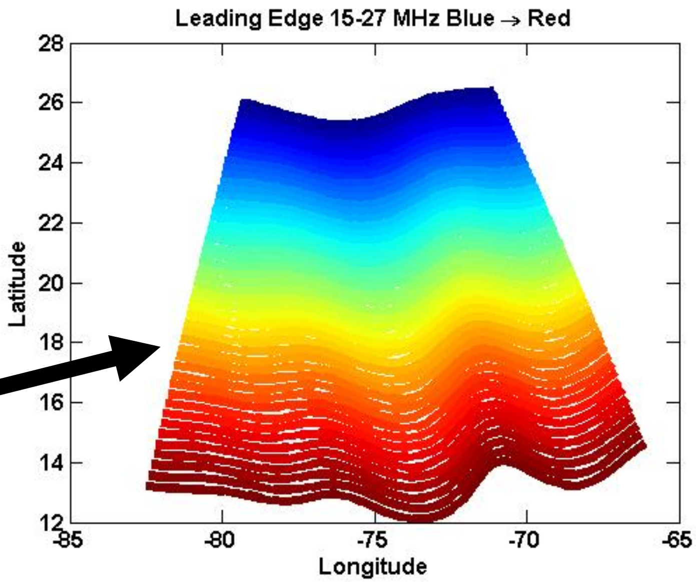
- Full-aperture WSBIs were collected on ROTHR by Dr. Geoff San Antonio (NRL) in an experimental configuration of ROTHR

# High-Resolution Leading Edge Data

**Color contours span 15 (blue) to 27 (red) MHz**




**Full aperture WSBI leading edge measurements collected by Dr. Geoffrey San Antonio (NRL)**




**Simulated WSBI leading edges using NWRA ray tracing in TID model**

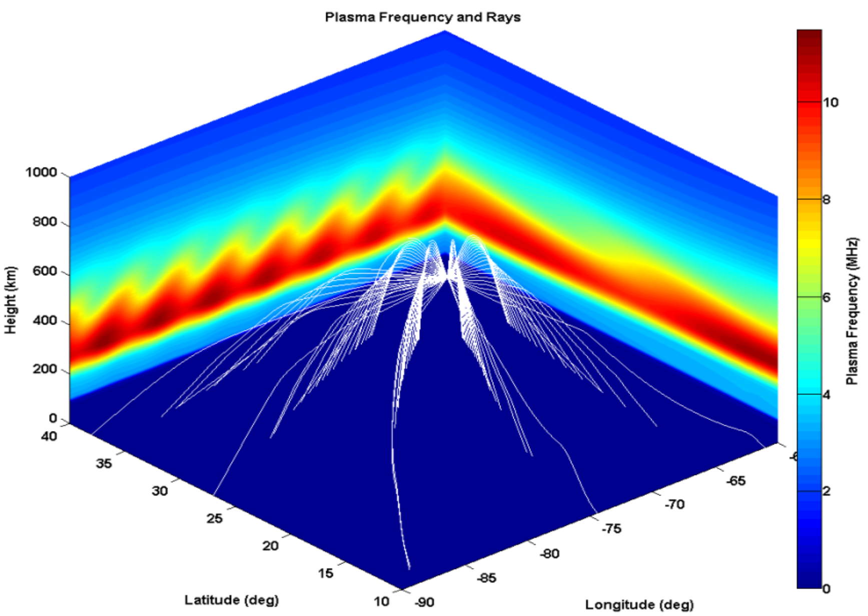
NWRA
Since 1984

# The Hooke TID model was incorporated into NWRA's ray tracing code

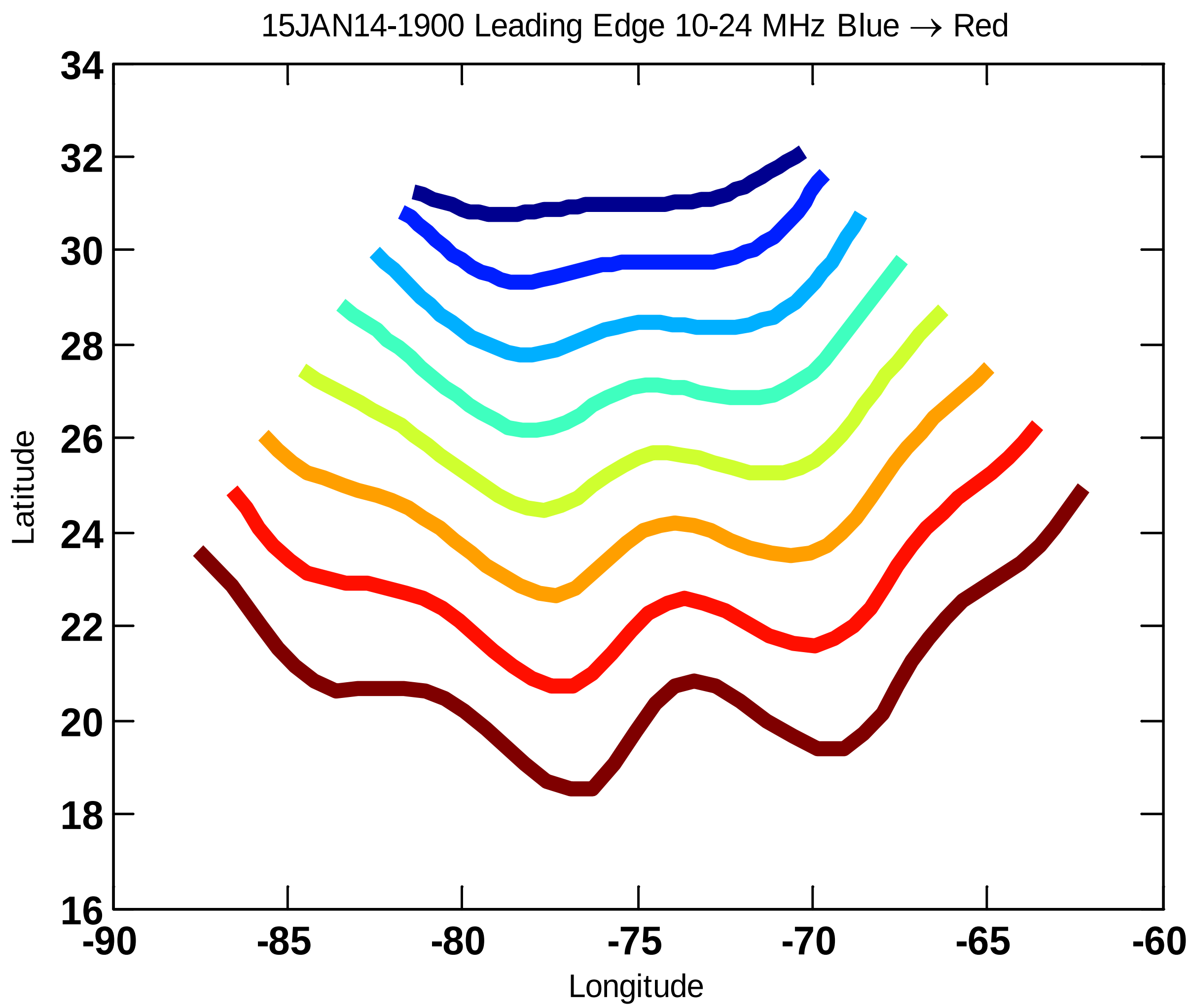
- Hooke, W. H., "Ionospheric irregularities produced by internal atmospheric gravity waves," Geophysical Monograph Series, *The Upper Atmosphere in Motion*, Vol. 18, pp. 780-808, 1968

$$N_e'(\mathbf{x}) = N_{e0}(\mathbf{x}) U_b(z_0) \sin(I) \exp(k_{zi}(z - z_0)) \omega^{-1} \sqrt{\left(\frac{\partial \ln N_{e0}}{\partial z} + k_{zi}\right)^2 + \left(\frac{k_{br}}{\sin I}\right)^2}$$

$$\exp\left\{ i \left[ \omega t - \mathbf{k} \cdot \mathbf{x} - \tan^{-1}\left( k_{br} \Big/ \sin I \left( \frac{\partial \ln N_{e0}}{\partial z} + k_{zi} \right) \right) \right] \right\}.$$



# Generated synthetic high-resolution WSBI leading edge data: Known truth data



# Modified GPSII to assimilate hi-res leading edge data

NWRA Since 1984

$$U_n = \gamma_1 U_{n-1} + \gamma_2 U_{n-2} + \nu_n$$

$$\gamma_1 = 2e^{-\frac{\Delta t}{\tau}} \cos\frac{2\pi\Delta t}{T}$$

$$\gamma_2 = -e^{-2\frac{\Delta t}{\tau_s}}$$

$$\gamma_1 = e^{-\frac{\Delta t}{\tau_s}} + e^{-\frac{\Delta t}{\tau_f}}$$

$$\gamma_2 = -e^{-\frac{\Delta t}{\tau_s}-\frac{\Delta t}{\tau_f}}$$

$$F(x) = \sum_{\alpha=-1}^{2} f_{i+\alpha} v_\alpha\left(\frac{x - x_i}{x_{i+1} - x_i}\right)$$

$$v_{[-1:2]}(t) = \frac{1}{2}\begin{bmatrix} -t^3 + 2t^2 - t \\ 3t^3 - 5t^2 + 2 \\ -3t^3 + 4t^2 + t \\ t^3 - t^2 \end{bmatrix}$$

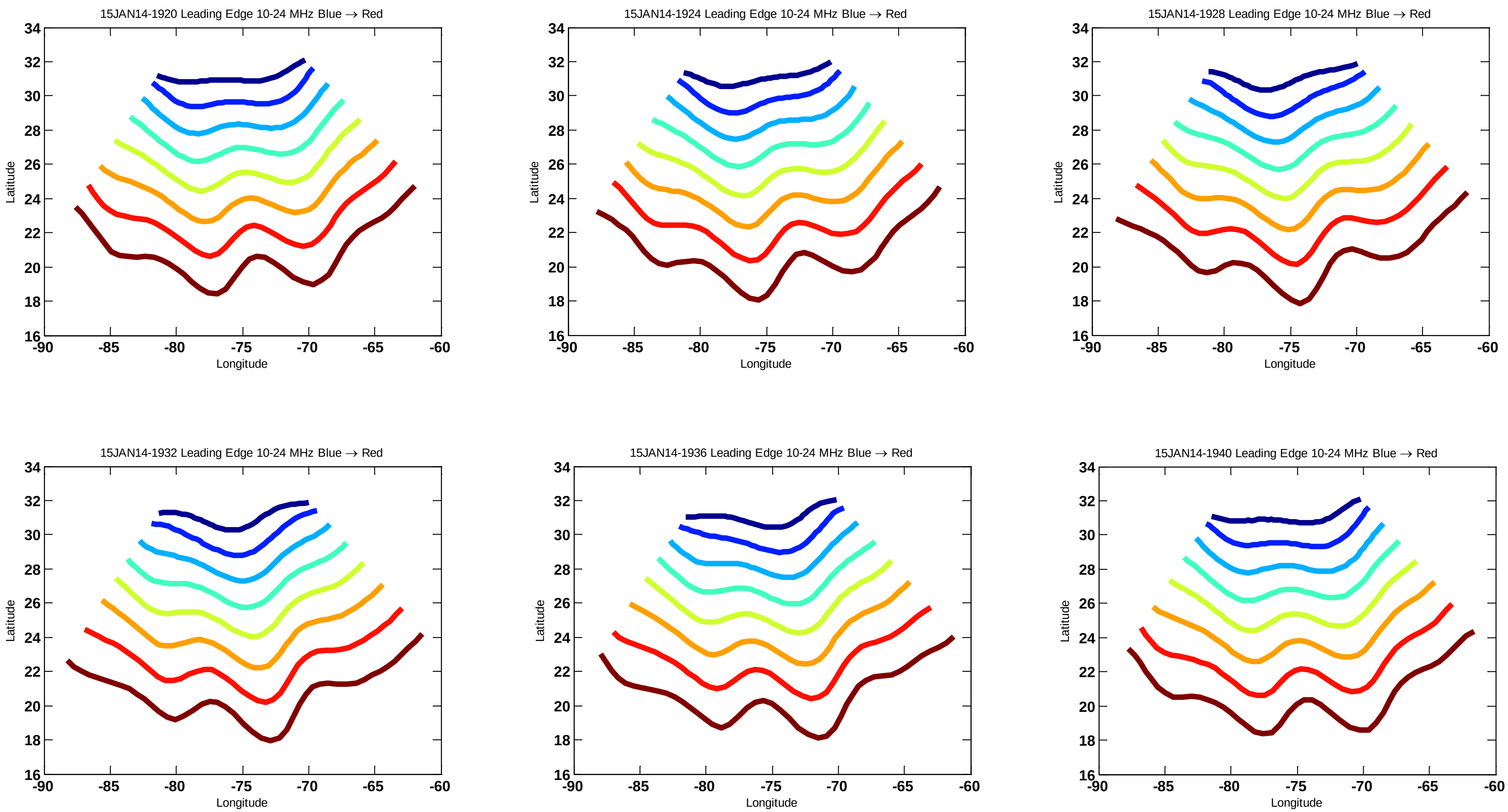
$$v_{[-1:2]}(t) = \begin{bmatrix} \frac{1}{d_-(1+d_+)}(-t^3 + 2t^2 - t) \\ (2 - \frac{d_+}{1+d_+} + \frac{1-d_-}{d_-})t^3 - (3 + 2\frac{1-d_-}{d_-} - \frac{d_+}{1+d_+})t^2 + \frac{1-d_-}{d_-}t + 1 \\ (-2 + \frac{d_-}{1+d_-} + \frac{d_+ - 1}{d_+})t^3 + (3 - 2\frac{d_-}{1+d_-} - \frac{d_+ - 1}{d_+})t^2 + \frac{d_-}{1+d_-}t \\ \frac{1}{d_+(1+d_+)}(t^3 - t^2) \end{bmatrix}$$

$$F(x,y,z) = \sum_{\gamma=-1}^{2}\sum_{\beta=-1}^{2}\sum_{\alpha=-1}^{2} f_{i+\alpha,j+\beta,k+\gamma} v_\alpha^x\left(\frac{x - x_i}{x_{i+1} - x_i}\right) v_\beta^y\left(\frac{y - y_j}{y_{j+1} - y_j}\right) v_\gamma^z\left(\frac{z - z_k}{z_{k+1} - z_k}\right)$$

$$x_i \le x < x_{i+1}, y_k \le y < y_{k+1}, z_k \le z < z_{k+1}$$

NWRA
Since 1984

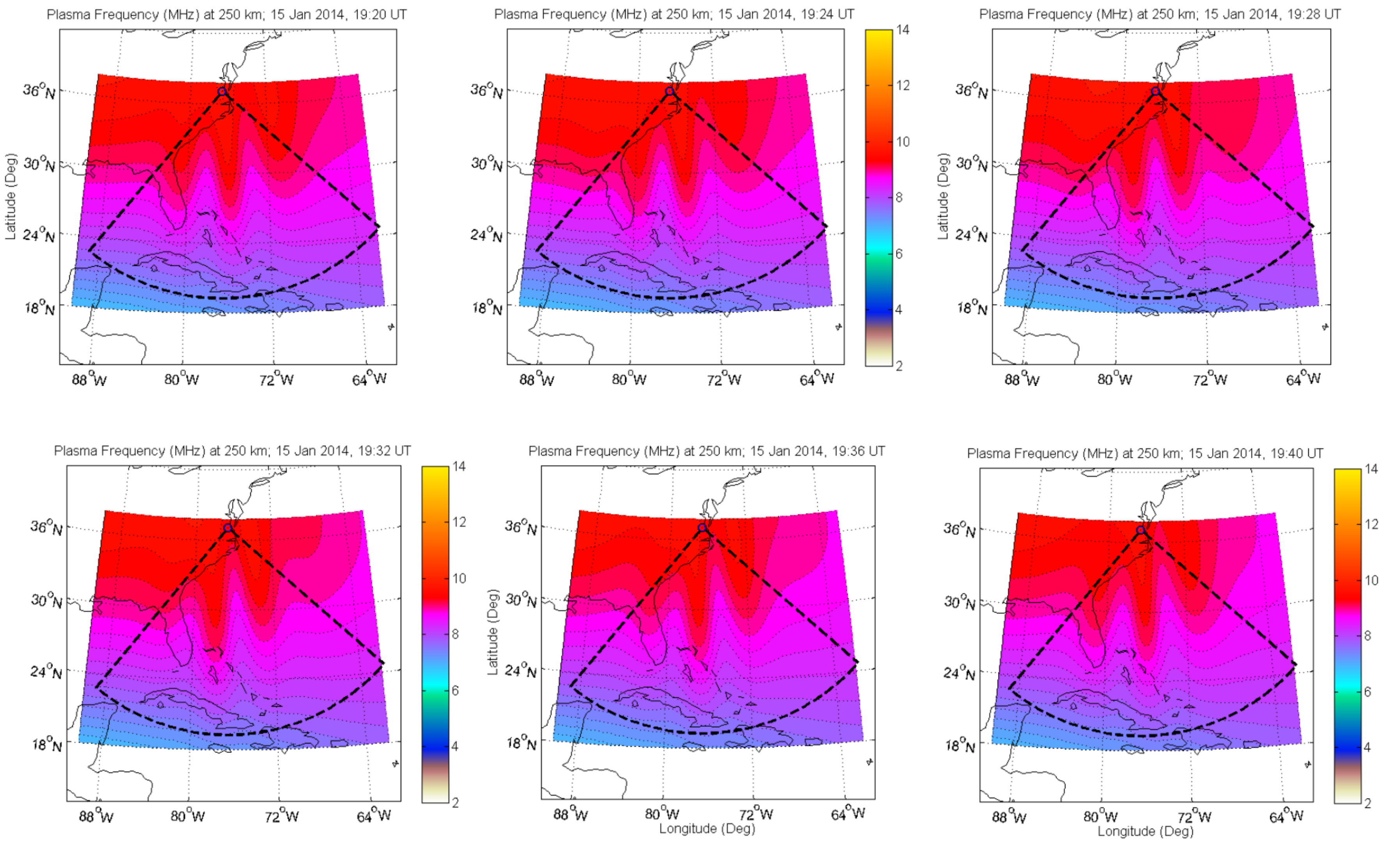
# Sample Input Data




**Samples separated by 4 minutes in time spanning 20 minute period of TID**

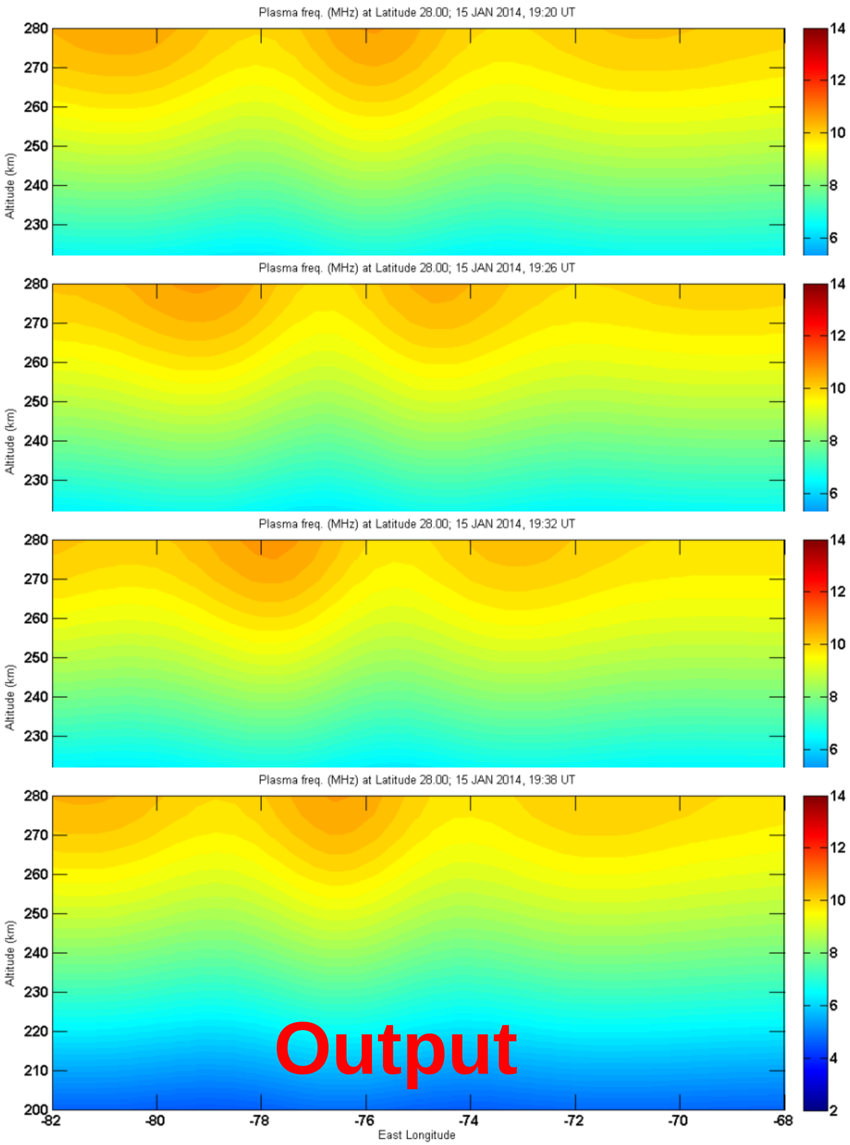
NWRA
Since 1984

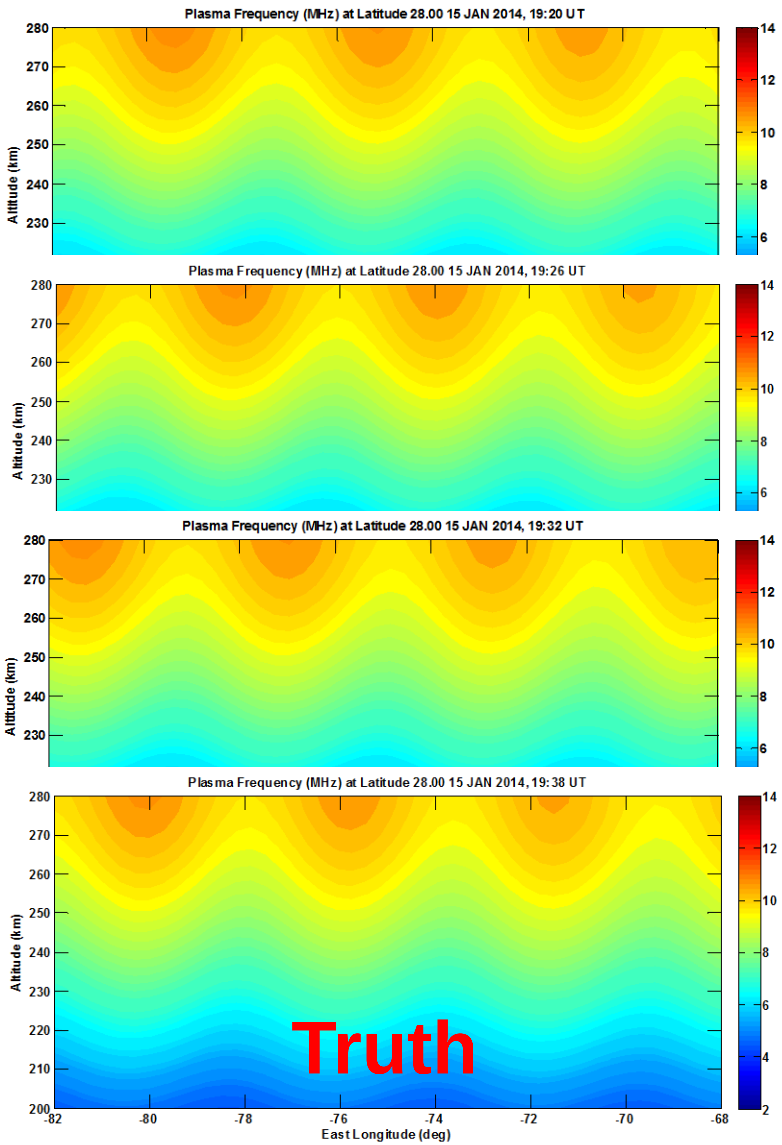
# Sample Output: Plasma frequency (MHz) at 250 km altitude



NWRA
Since 1984

# Comparison of Output to Truth



NWRA
Since 1984

# Future plans

- Result of synthetic feasibility study is encouraging
- This work will continue over the next two years
  - Collect full aperture WSBI data on ROTHR in conjunction with fixed transponder data
  - Add capability for assimilating surface clutter Doppler data
  - Field and ASTRA TIDDBIT system in the field of view of ROTHR to collect independent TID data for comparison (Dr. Geoff Crowley)