Improved Modeling and Prediction of Total Atmospheric Refractivity by Assimilation of Angle of Arrival and Total Electron Content Measurements from an Array of GPS Receivers

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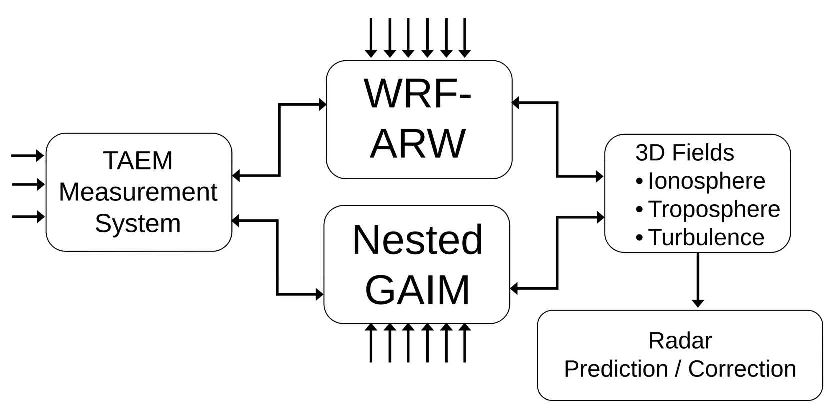
Introduction

The Total Atmospheric Effects Mitigation (TAEM) system measures atmospheric effects on GPS signals and then assimilates those measurements into both tropospheric and ionospheric models in order to determine current and forecast atmospheric states. TAEM hardware includes multiple ground-based, dual-frequency GPS receivers in an array. Use of multiple receivers extends performance to elevations below 10 degrees, where multipath effects typically corrupt GPS signal quality. Measurements of the difference between observed and expected angle of arrival are assimilated into the Weather Research and Forecasting (WRF) model, improving the model's fidelity of temperature, pressure, and humidity, while measurements of total electron content are assimilated into the Jet Propulsion Laboratory/University of Southern California's Global Assimilative Ionospheric Model (GAIM), improving that model's fidelity of ionospheric electron densities. Such joint assimilation has the potential to improve the characterization and prediction of the local refractivity field from the earth's surface up to the upper atmosphere, which would lead to improved atmospheric corrections to electromagnetic signals of interest.

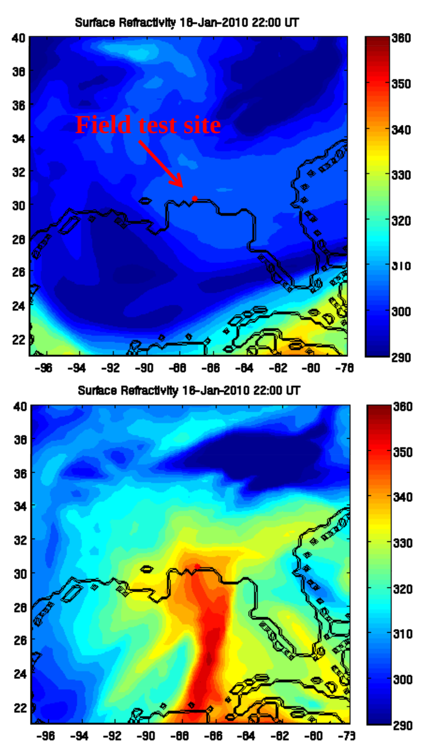
We present results from a field test of the TAEM system performed in January, 2010. Although the ionosphere was quiet during this period due to solar minimum, benefits are still apparent from using the recently developed nested-grid capability of GAIM to create a higher resolution representation of the ionosphere in the local area of the TAEM hardware.

TAEM System Overview

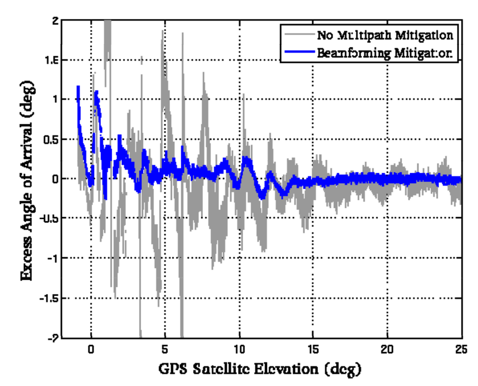
The TAEM system starts with the measurement of GPS signals using an array of 8 antennae. Excess angle of arrival is then assimilated into a tropospheric model (WRF-ARW), and slant total electron content (TEC) is assimilated into an ionospheric model (NGAIM). Model outputs are used to create a 3-dimensional refractivity field, from which corrections can be computed for signals of interest.



Tropospheric Refractivity



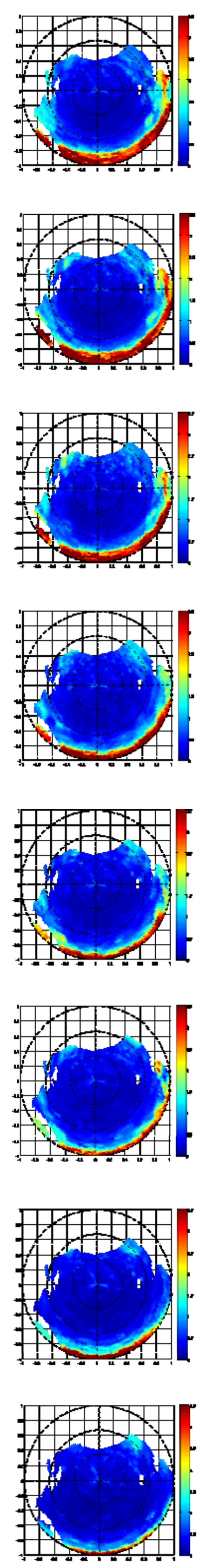
Apparent angle of arrival (AoA) is primarily affected by the troposphere. Climatological corrections do not account for the sorts of variations in refractivity seen in the two plots to the left, which were generated from WRF output for the same time at two different days during the field test. Assimilating measured AoA into WRF improves the model's accuracy, further improving corrections. As demonstrated below, using the full 8-antenna array mitigates multipath effects on excess AoA measurements when compared to using any 2 antennas.

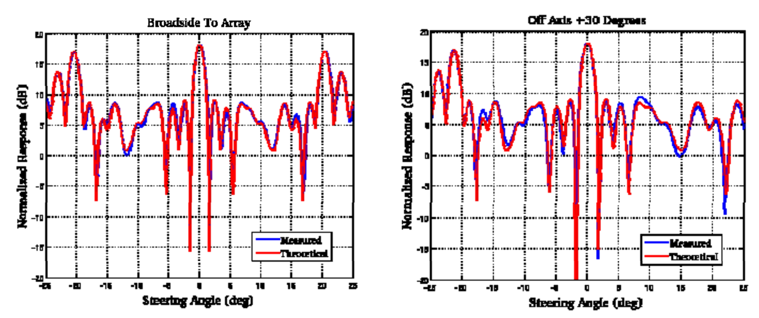


TAEM Measurement System

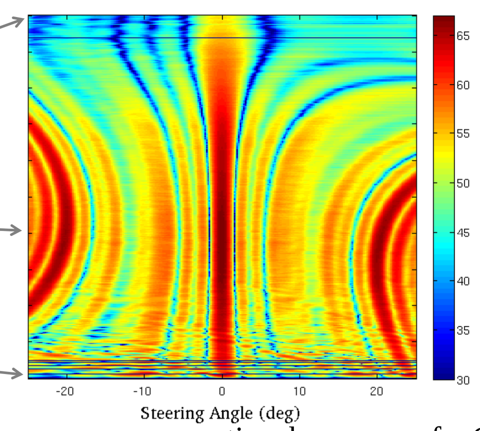
A view of PRA's GPS antenna array at a field test on Pensacola Beach, FL in January, 2010. 8 antennae are surrounded by absorbing material and supported on a structure that tilts the array back by 45 degrees.

L1 signal-to-noise variation (dB) for individual receivers

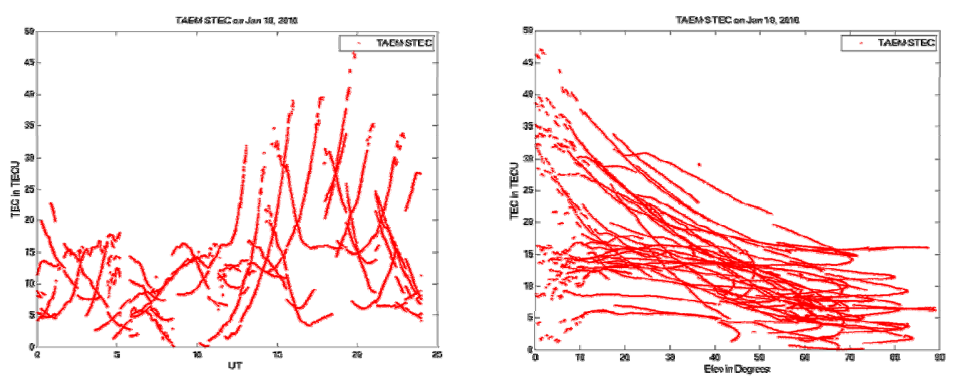




Measured and theoretical array response (signal-to-noise ratio) as the "look" direction is mathematically steered. Steering Angle=0 is looking directly at the target GPS satellite. Positive angles indicate the antenna is looking towards higher elevations; negative angles are towards lower elevations. As the satellite travels away from broadside (elevation=0 in the array coordinate system), the antenna pattern becomes asymmetrical.



Measured array response over an entire sky sweep of a GPS satellite. Horizontal cross-sections give the response curves seen above. Response is close to theoretical except when the satellite approaches the horizon, where multipath contributions are seen.

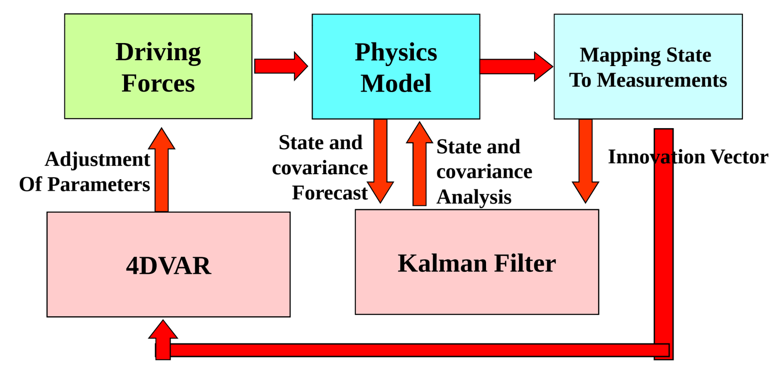


Slant TEC versus time (left) and elevation (right) for array data taken January 18, 2010. TEC was determined from L1 and L2 observables using JPL's Global Ionospheric Model software. Although the data become sparse below 10 degrees as signal is periodically lost in one or more receivers, the trends of the curves look reasonable.

Ionospheric Refractivity Model

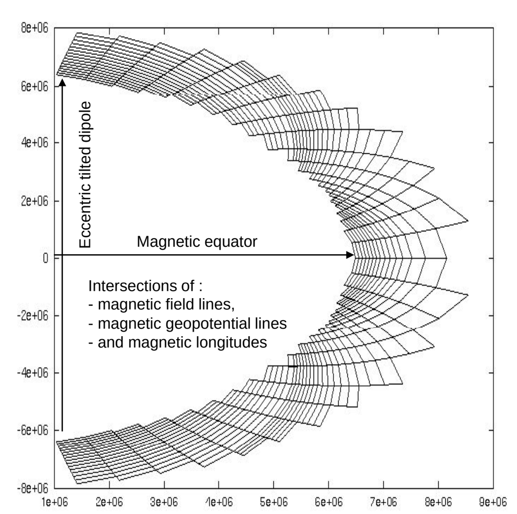
NASA's Jet Propulsion Laboratory has improved the Global Assimilative Ionospheric Model (GAIM) to allow for site-specific resolution improvement using nested grids (NGAIM). This improved model assimilates slant TEC as measured by the TAEM system to provide dynamic updates for correction of ionospheric refractivity effects.

NGAIM Estimation Processing

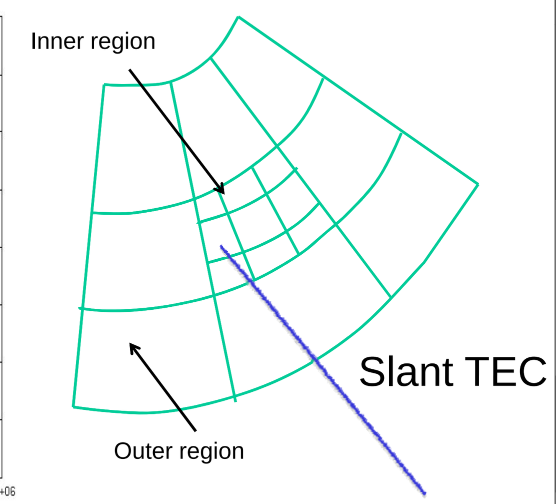


- 4-Dimensional Variational Approach
  - **Minimization of cost function by estimating driving parameters**
  - **Non-linear least-square minimization**
  - **Adjoint method to efficiently compute the gradient of cost function**
  - **Parameterization of model "drivers"**
- Kalman Filter
  - **Recursive Filtering**
  - **Covariance estimation and state correction**
  - **Optimal interpolation**
  - **Band-Limited Kalman filter**

Ionospheric Global and Nested Grids

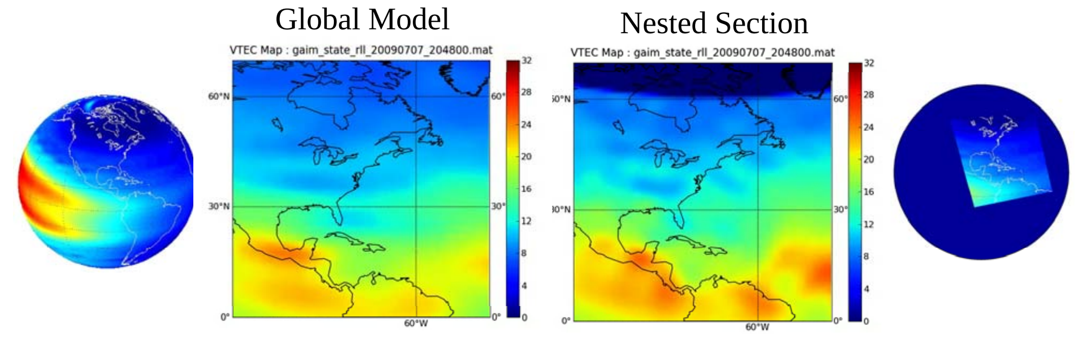


The Global GAIM Grid



Schematic of a Nested Grid

Increased Resolution With Nested Grid



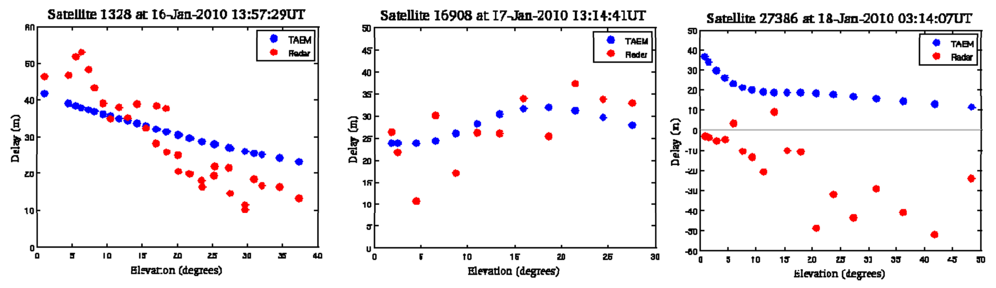
Using the 3-D Refractivity Field

A fully 3-dimensional refractivity field is created by calculating refractivity from pressure, temperature, and water vapor (from WRF output) and electron density (from NGAIM output). The last component of the TAEM system involves raytracing through this field to produce range and angle of arrival corrections to supply to the radar.

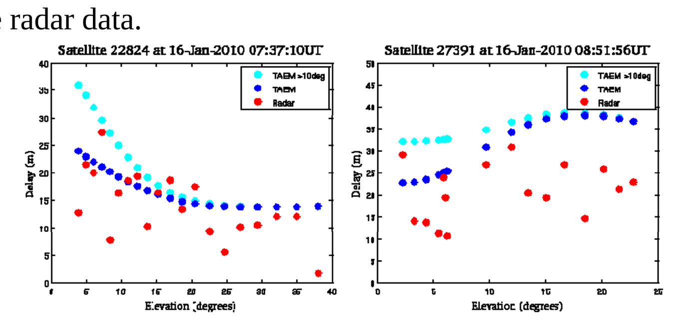
$$\frac{d}{ds}\left(n\frac{d\vec{r}}{ds}\right)=\nabla n$$

Comparing to Radar Data

Concurrent with the TAEM field test, the AN/FPS-85 radar at Eglin Air Force Base in Florida observed satellites in orbit. With all corrections applied to the radar measurements except for the ionosphere, the difference between the apparent range and the true range is a measure of ionospheric effects. As shown in the three plots below, TAEM-derived ionospheric effects do a reasonable job reproducing the shape of the ionospheric effects on the radar signal over a range of elevations. The comparison is hampered by radar scatter, unexpected negative radar values (rightmost plot), and the low solar activity at the time of the field test. For these results, data from TAEM were the only data assimilated into the NGAIM runs.



We tested the effects of low-elevation TAEM data by doing NGAIM runs excluding all observations below 10 degrees. For times when GPS measurements were made near the satellite observations, the low-elevation data made a noticeable improvement in the TAEM agreement with the radar data.



Difference between TAEM-derived ionospheric effects and radar-derived effects comparing using the higher-resolution nested grid with the global grid.

	All Elevations			Elevation < 10 degrees		
	Mean	Stdev	RMS	Mean	Stdev	RMS
Nested Grid	15.6	14.5	21.3	10.3	12.8	16.3
Global Grid	18.8	14.2	23.5	16.5	13.0	20.9

Conclusion

PRA has developed a 3-D refractivity field using the WRF and NGAIM simulations. The refractivity field can be used to predict corrections to signals of interest. PRA worked closely with JPL as they add nested-grid capability to GAIM, which is shown to improve the fidelity of ionospheric corrections derived from the refractivity field. PRA's TAEM measurement system successfully measures excess angle of arrival and slant TEC at elevations above and below 10 degrees.

Acknowledgments

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