A Joint Estimation Approach for the Geolocation of Ground HF Transmitters in the Presence of Ionospheric Perturbations*

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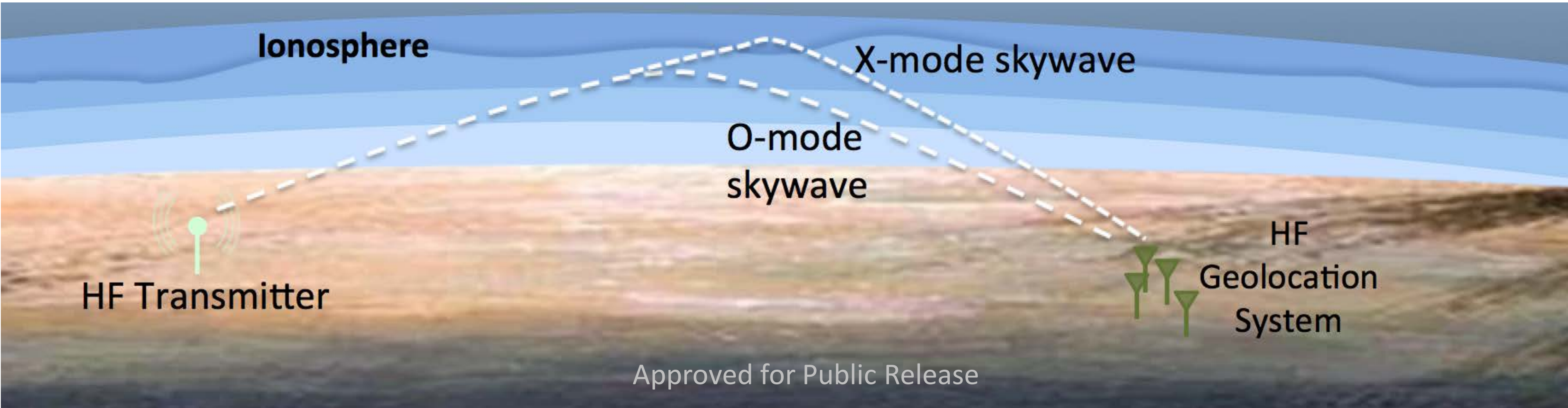
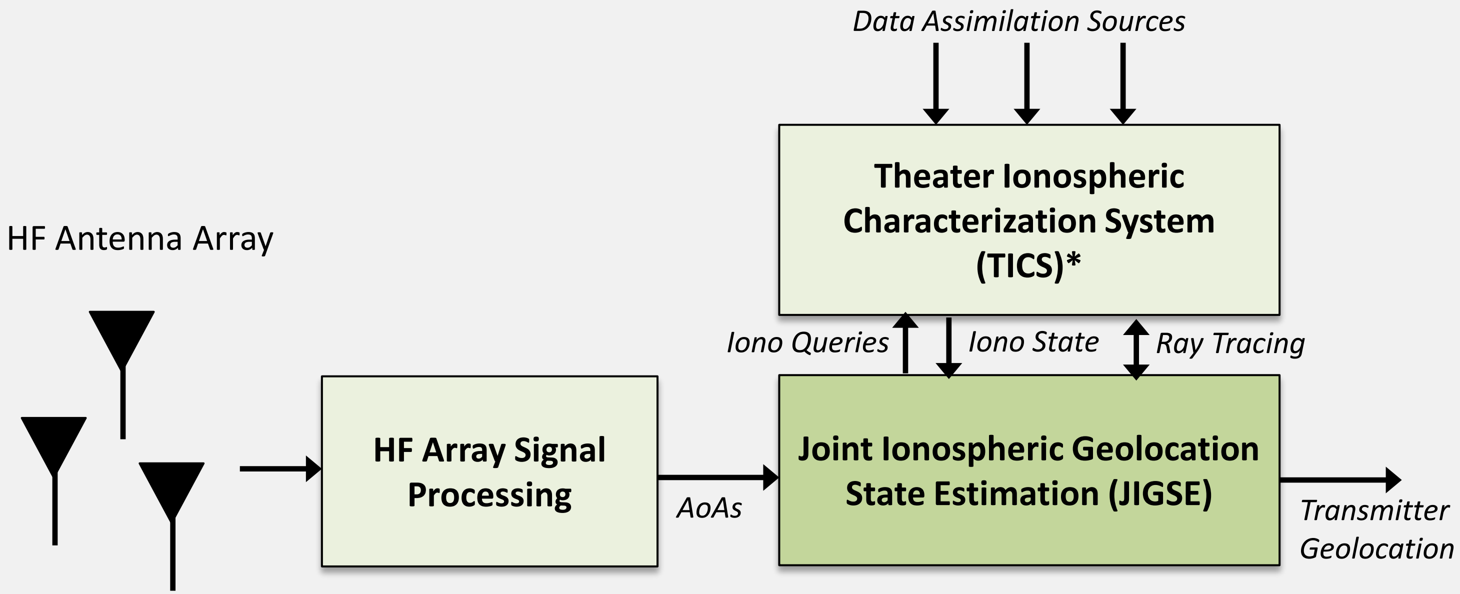
High Frequency Geolocation (HFGeo) Program

- HFGeo Problem: Locate RF transmitters communicating over long ranges via low-cost HF transmissions
- Standard single-site geolocation approach: Ray trace from received angles of arrival (AoA) through precise ionospheric model to estimate HF transmitter position
- Challenge: Precise models require active ionospheric probing at midpoint of link (which is unknown) and are sensitive to complex propagation modes, Traveling Ionospheric Disturbances (TIDS), and noise sources
- STR Approach: Jointly estimate ionospheric and transmitter states leveraging received skywave angle of arrival (AoA) measurements



HF Geolocation System Components



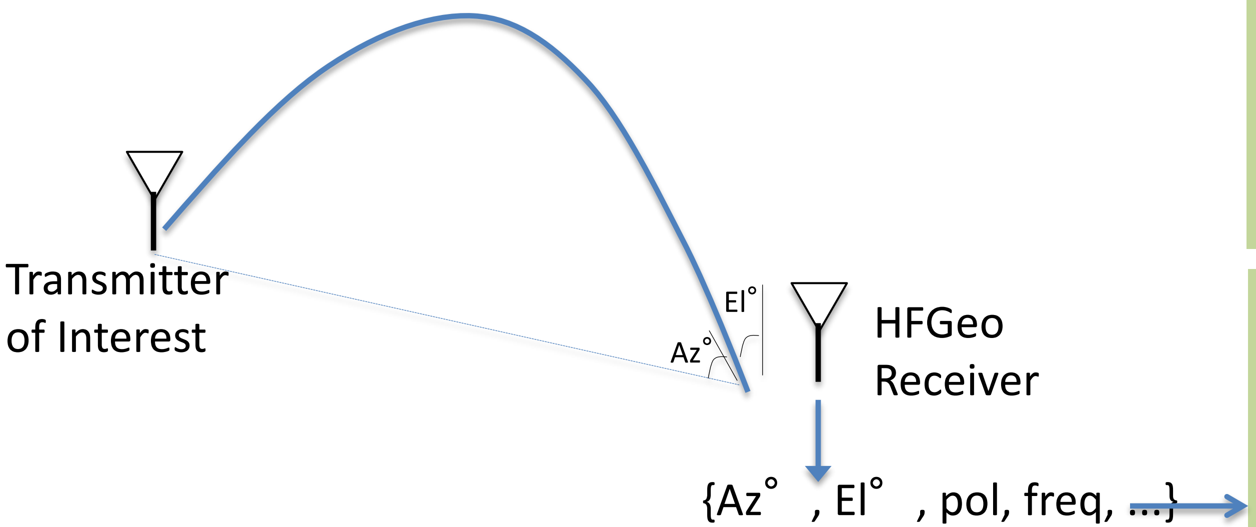
- TICS includes the Regional Optimum Assimilation Model (ROAM), see *Carrano et al* paper

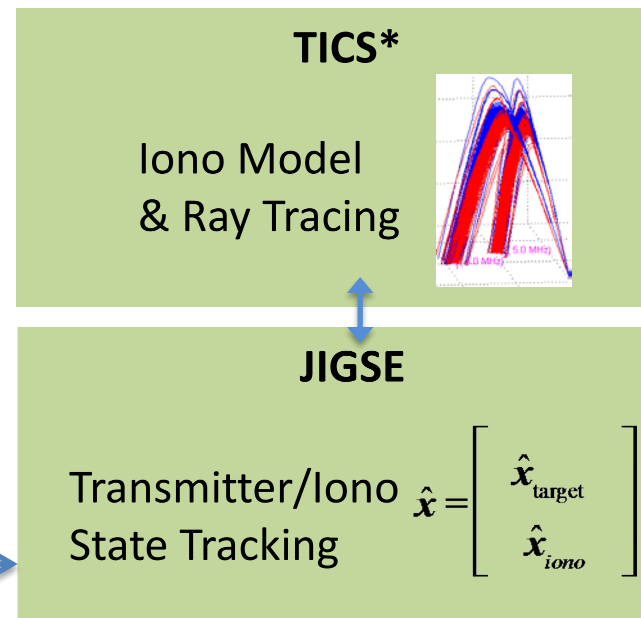
- **Joint estimation of transmitter location and ionospheric state using received skywave signals enables high-accuracy transmitter geolocation**
  - **Ionospheric model provides state information from background model and (when available) data assimilation sources (sounders, check targets, GNSS)**
  - **High accuracy all-passive HF geolocation achievable through joint estimation**

- **Key innovation is the exploitation of the fact that transmitter skywaves reveal information about the Tx location and the propagation channel**

How Does Joint Estimation Work?

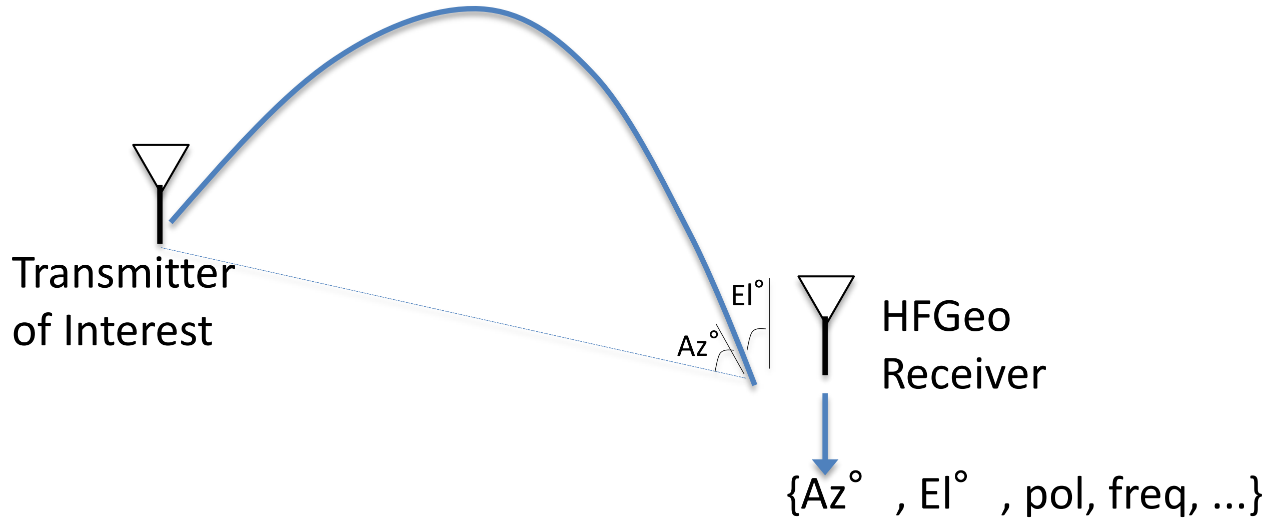
- **Joint Ionosphere-Geolocation State Estimator (JIGSE): use non-linear estimation and tracking techniques to exploit skywave combined measurement of the transmitter location and ionospheric state**
  1. **Each AoA measurement is a function of *transmitter location* and the *current state of the ionosphere***
  2. **Use a perturbation technique (Unscented Kalman Filter) to propagate transmitter and ionosphere state and covariance**
  3. **Over time, state estimates will converge**





*The results published in this paper were obtained using the HF propagation toolbox, PHaRLAP, created by Dr Manuel Cervera, Defence Science and Technology Group, Australia (manuel.cervera@dsto.defence.gov.au). This toolbox is available by request from its author

Step 1 – Sample Transmitter and Ionosphere State Space

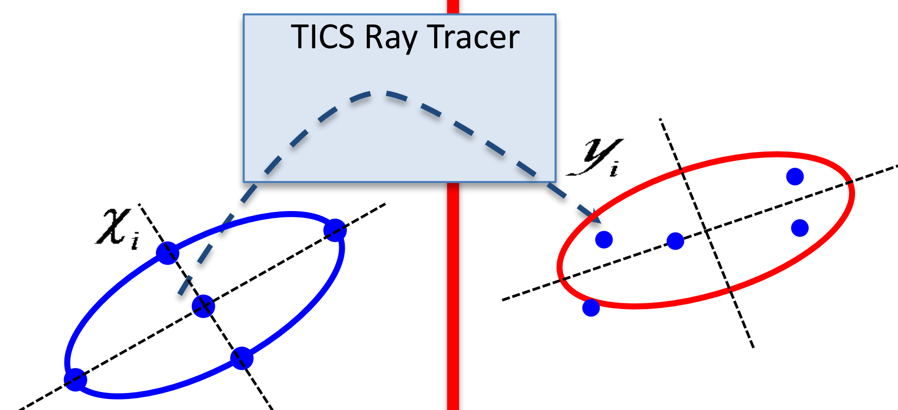


Non-linear Estimation – Unscented Kalman Filter

Transmitter/Iono State Vector

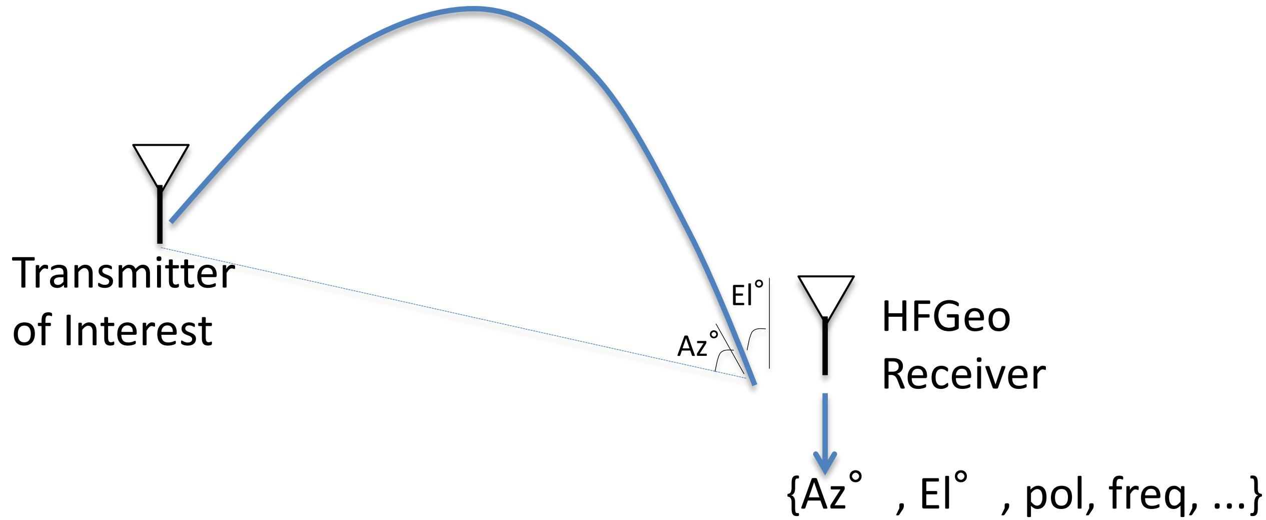
$$\hat{x} = \begin{bmatrix} \hat{x}_{target} \\ \hat{x}_{iono} \end{bmatrix}$$

1. Start with Predicted Transmitter/Iono State
(On first iteration, initialized from 1st measurement)

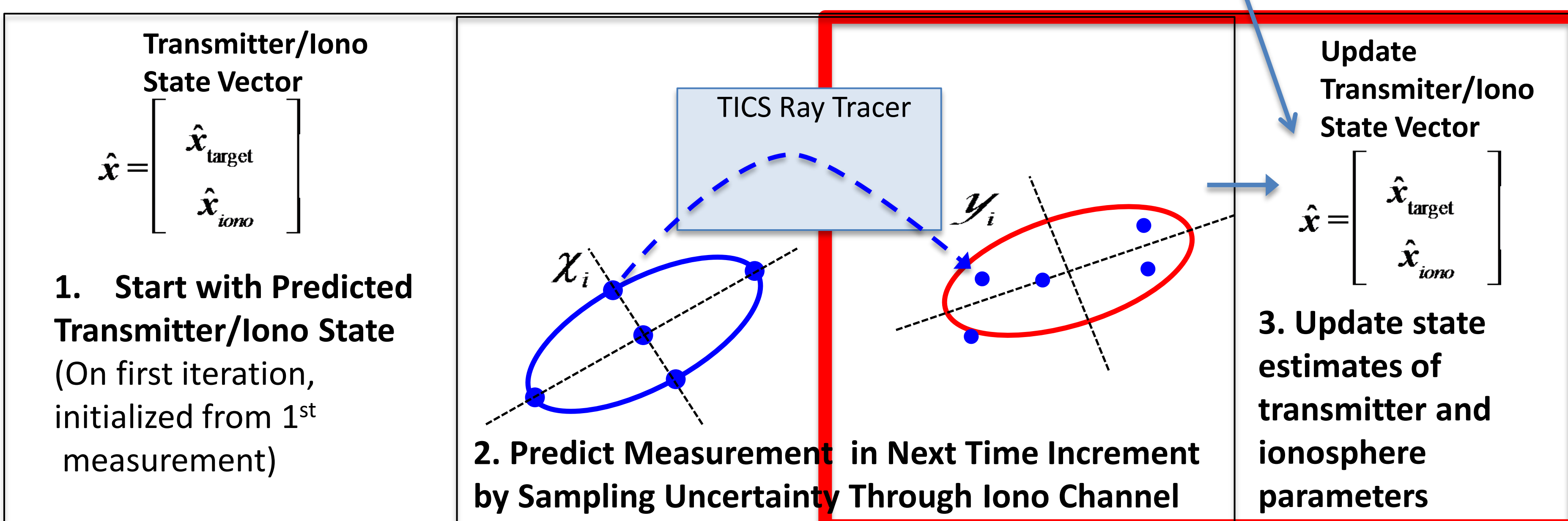


2. Predict Measurement in Next Time Increment by Sampling Uncertainty Through Iono Channel

Steps 2 and 3 – Predict Measurement and Update Joint State



Non-linear Estimation – Unscented Kalman Filter

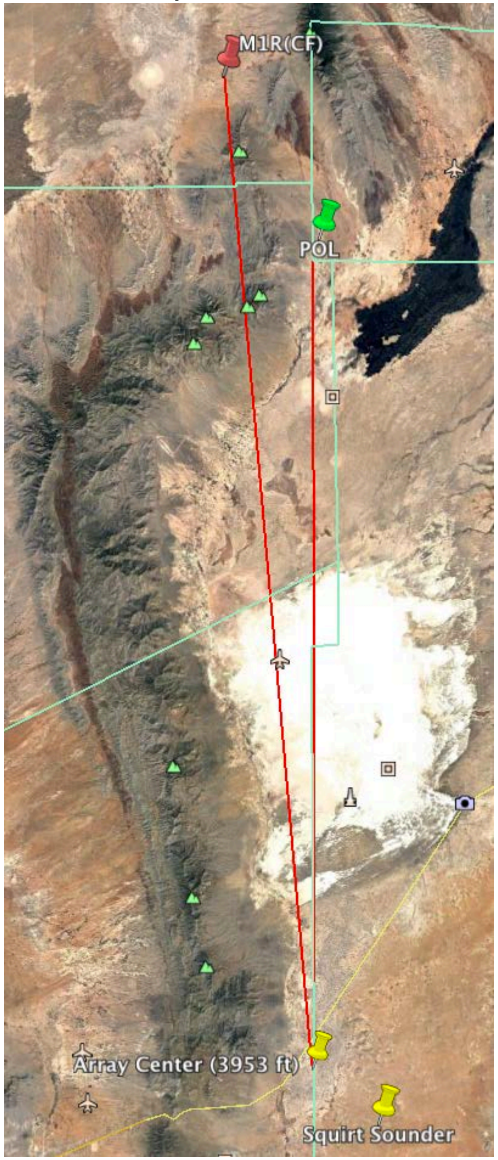


HFGeo Results from White Sands Missile Range (WSMR) Data Collects

- **Data collected over multiple days on Jan. 2014 and March 2016 at WSMR**
  - **Government antenna array composed of bow-tie antennas at G10 site**
  - **Angle of Arrivals (AoAs) computed by Government team**
- **Results shown next correspond to two transmitters located ~ 100 – 150 km from receiver site (Jan 19 2014 - POL Tx and June 20 2016 - M1RCF Tx data sets)**
- **We compared our passive-only ionospheric state estimates (plasma frequency plus tilt) with those provided by *ROAM* using measurements from a digisonde co-located with one of the Tx**

> - **JIGSE-estimated ionospheric state demonstrates "passive-only" ionosphere estimation capability at received transmitter frequency**

Transmitter/Receiver locations



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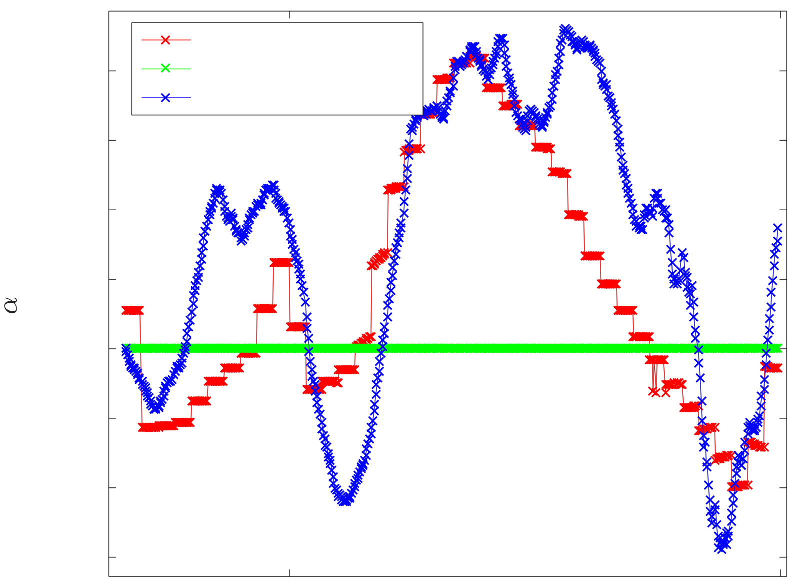
Passive Ionospheric Tilt Coefficient Estimate
Example 1 - Jan 19 2014, POL Tx

- **Linear tilt parametric model given by a North/South gradient and an East/West gradient**

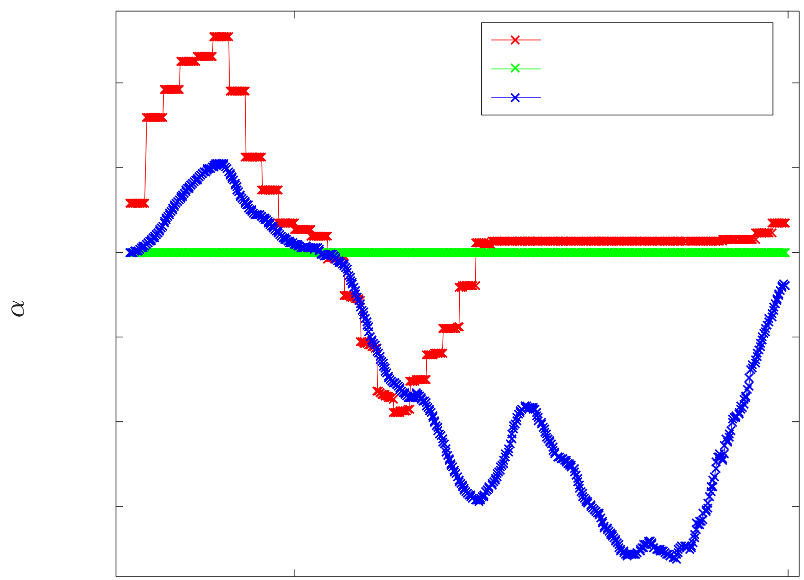
$$f_p(h,lat,lon) = f_p^0(h,lat_0,lon_0)A(h)\left[1+\alpha_{lat}(lat-lat_0)\right]\left[1+\alpha_{lon}(lon-lon_0)\right]$$

- **Good overall match of tilt coefficients – note that the East/West ROAM tilt coefficient is zero during the second part of the collect due to an issue with the processing of the skymaps produced by the Digisonde**

North/South tilt coefficient vs time



East/West tilt coefficient vs time

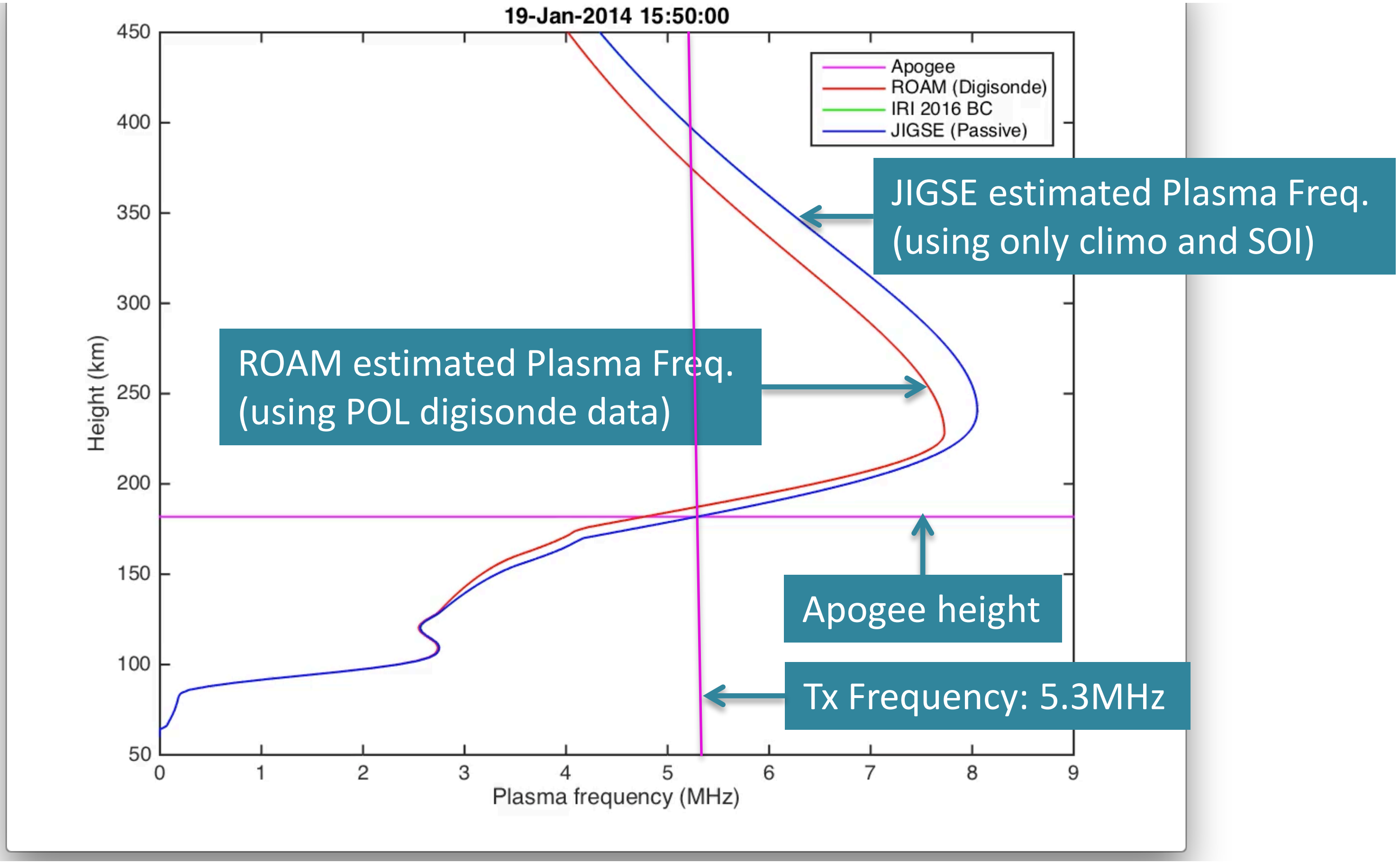


Passive Plasma Frequency Profile Estimate
Example 1 - Jan 19 2014, POL Tx

- **JIGSE estimated only a subset of the IRI parameters**

$$\textbf{IRI Reduced model} = [foF2, foF1, foE, hmF2, B0, B1]$$

- **We compared JIGSE passively estimated profile with the one provided by ROAM (using POL Digisonde measurements)**



Plasma Frequency Profile Comparison

January 19 2014, POL Tx

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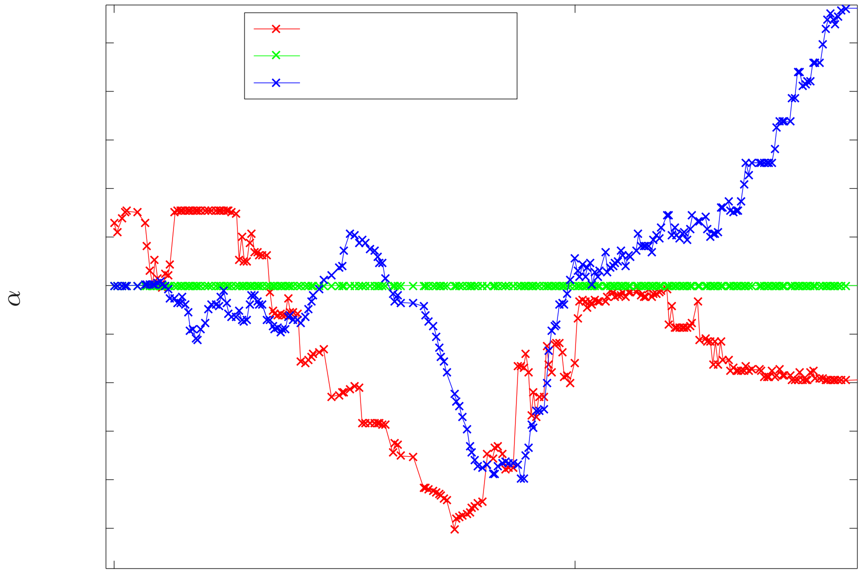
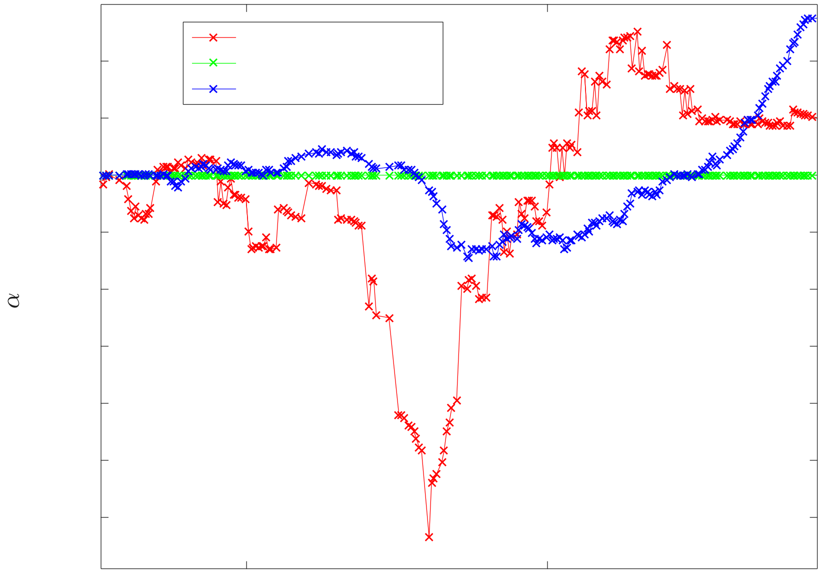
Passive Ionospheric Tilt Coefficient Estimates
Jun 20 2016, M1RCF Tx

- **Good overall matching of tilt coefficients (JIGSE vs ROAM/digisonde), particularly for North/South during first part of the data collect**
- **There is some divergence towards the final part of the collect, particularly for the north/south tilt**

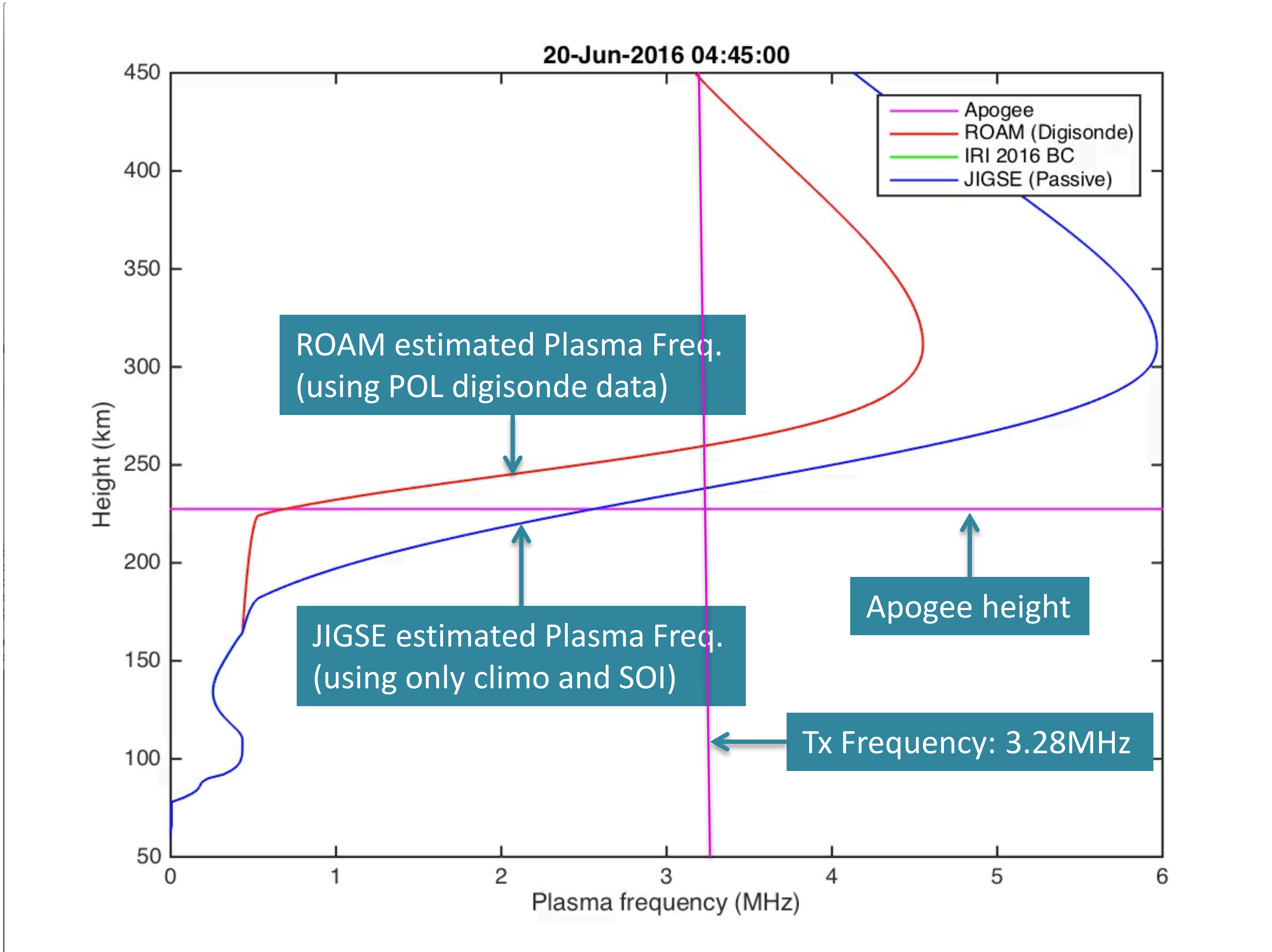
North/South tilt coefficient vs time



East/ West tilt coefficient vs time



Plasma Frequency Profile Estimate
June 20, 2016, 04:45



Plasma Frequency Profile Comparison

June 20, 2016, 04:45

Summary

- **Developed Joint Ionospheric Geolocation State Estimation (JIGSE) system to achieve accurate HF Transmitter geolocation**
  - Leveraging the fact that HF skywaves reveal information both of the Tx location and the propagation channel
  - Enables accurate state estimation when assimilation sources available, and also when operating in all-passive mode

- **Capability developed and demonstrated using data from HFGeo tests at WSMR**
  - JIGSE inputs include AoA's produced by Government team
  - Data collected during multi-week campaigns in January 2014 and June 2016
  - JIGSE geolocation results achieved HFGeo program metrics

- **JIGSE ionospheric state estimates computed for cases with no assimilation sources demonstrate passive ionosonde**
  - Tilt coefficient estimates match well to those measured by Digisonde and estimated in ROAM
  - Plasma frequency estimates converge to sounder measurements and show predictive capability

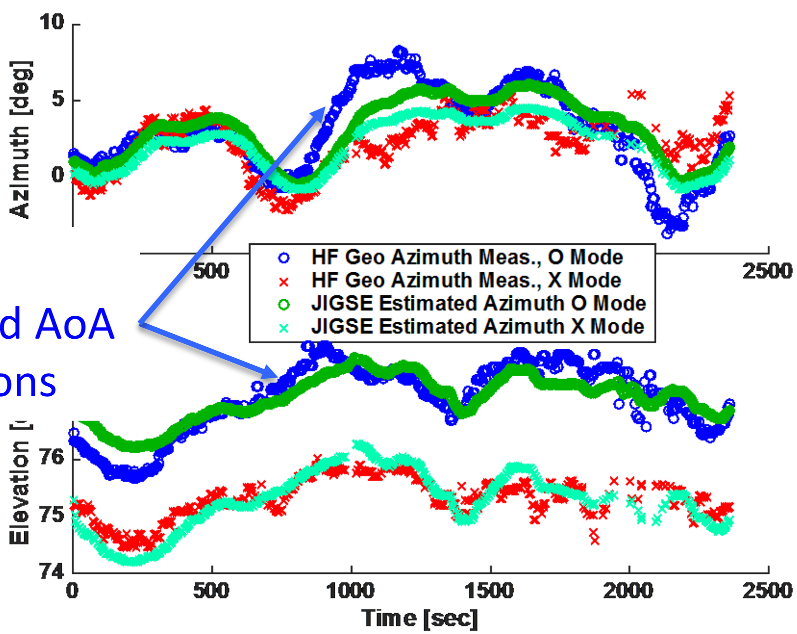
Backup slides

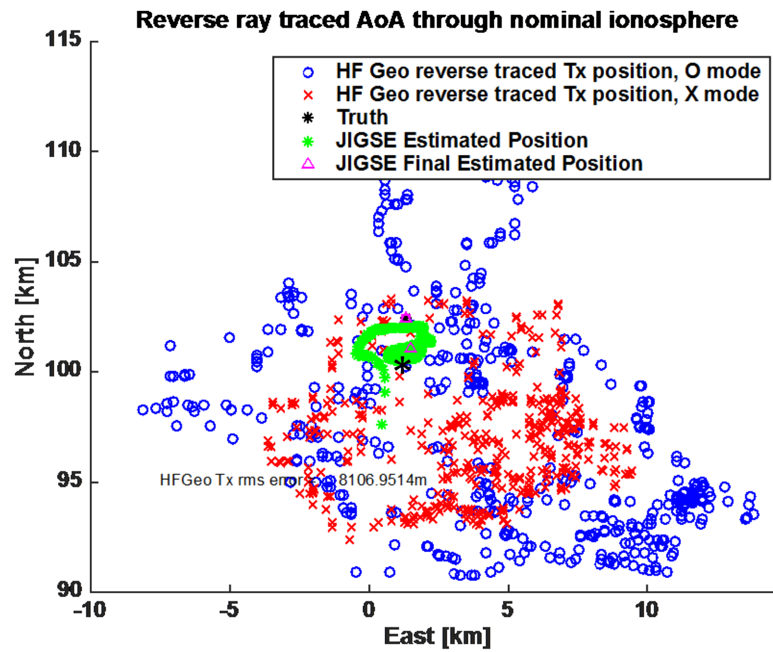
All-passive JIGSE TIDS Estimation Provides Pinpoint Geolocation Accuracy

SYSTEMS & TECHNOLOGY RESEARCH

Phase 1B data: Jan 2014 POL transmitter under average TIDS conditions

TIDS
induced AoA
variations





All-passive JIGSE TIDS estimation achieved a 1.5 km rms error, considerable smaller than the 8.1 km rms error obtained with reverse ray tracing using only a climatological model

Simultaneous Exploitation of All Propagation Modes Significantly Reduces Geolocation Errors

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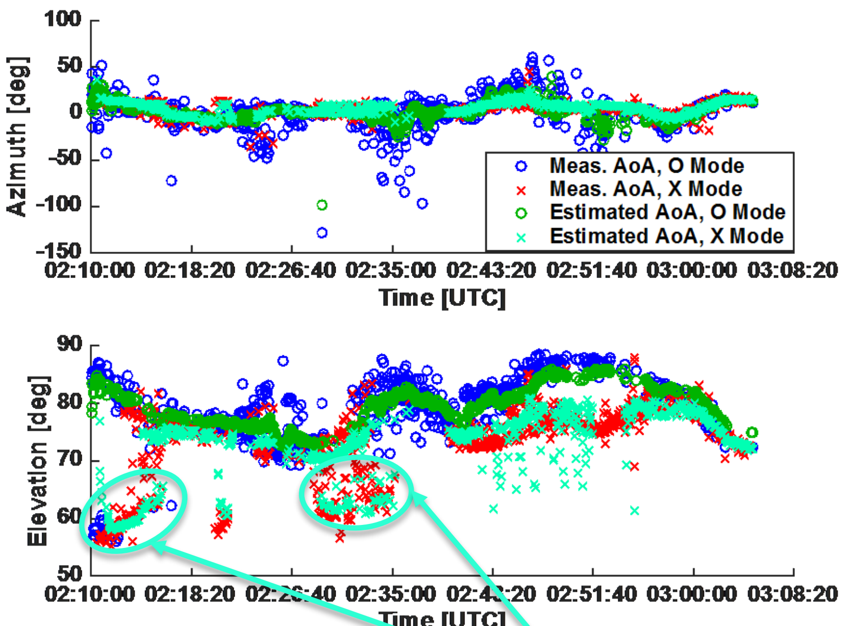
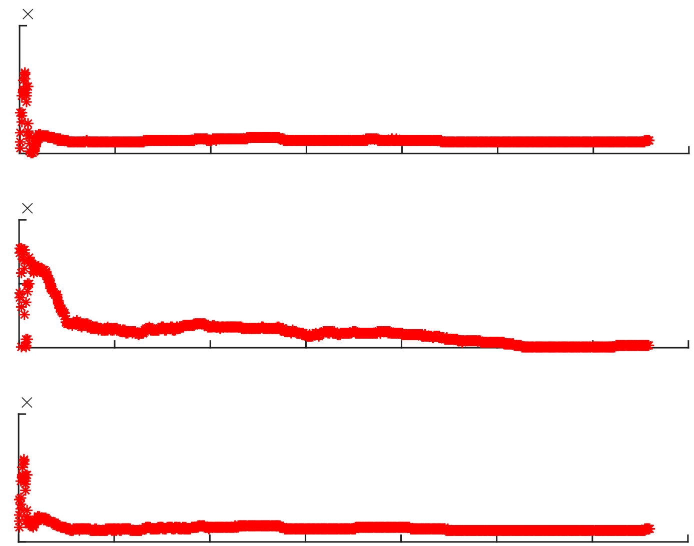
Phase 2A data: June 20, 2016 ORCN transmitter in the presence of sporadic E layer



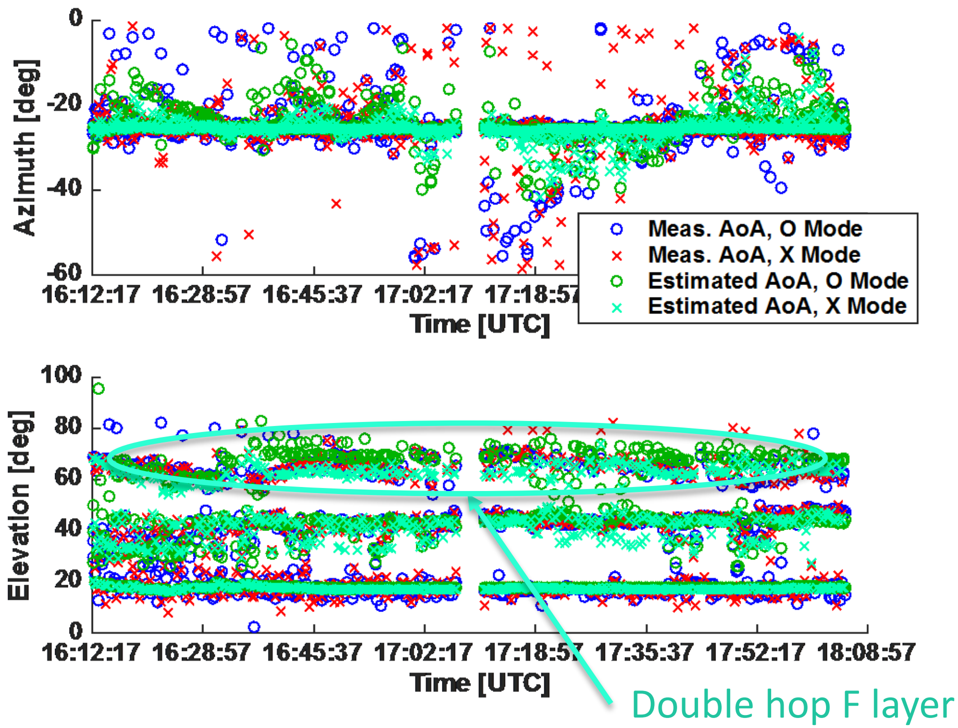


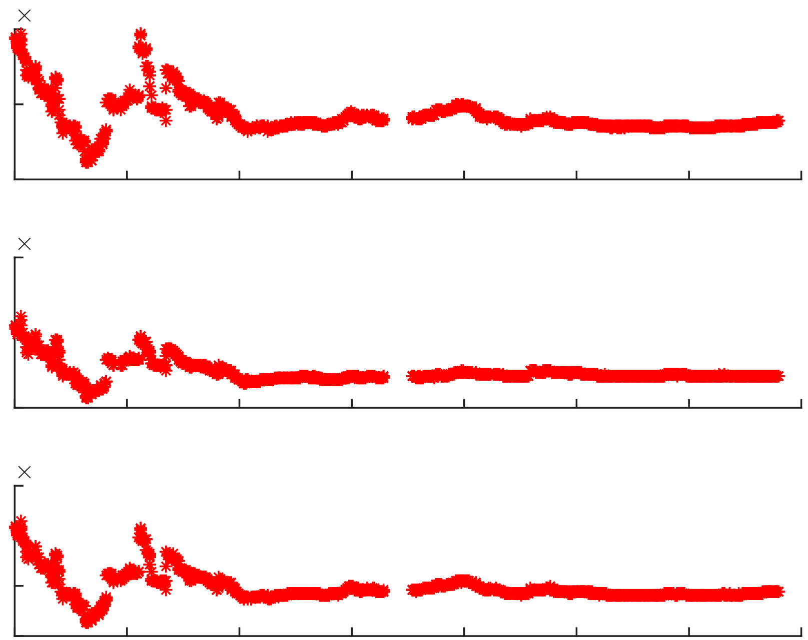
Modeled E layer X-mode ray path

Incorporating a sporadic E layer propagation mode resulted in a 9km RMS error (all passive) for a near range Tx

Simultaneous Exploitation of 3 Propagation Modes

Phase 2A data: June 15, 2016 Blanding (UT) transmitter in the presence of E, F and 2F propagation paths





Correct propagation mode characterization resulted in a 43.9 km rms error (all passive) for a far range Tx