Assimilation of HF Measurements of Unknown Sources for Improved HF Geolocation in the Presence of Traveling Ionospheric Disturbances

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Known and Unknown Reference Points

- **Known Reference Point (KRP) – radar detections associated with a target at known geographical location**
- **Unknown Reference Point (URP) – radar detections associated with a target at unknown geographical location**
  - **One URP set is a sequence of radar detections associated with the same unknown target**
  - **Each URP is specified by a 4-component unknown vector (latitude, longitude, latitude rate, and longitude rate)**
    - **May or may not be a target of interest for geolocation**
- **Assimilation of URP within ionospheric inversion is simultaneous estimation of the ionospheric model and target tracks**
  - **Simultaneous target geolocation and channel estimation was originally suggested by (*Li & Krolik* 2014) for a different system**

HF Propagation Data within GPSII

-The non-linear inverse problem is solved iteratively as a sequence of linear problems. At the iteration *n* the non-linear functional $M[U]$ is approximated by a linear operator L as follows

$$M[U] = M[U_{n-1}] + L(U - U_{n-1}) + o(\|U - U_{n-1}\|) \qquad \Leftrightarrow L = \delta M / \delta U$$

- L is the Ray Path Response (RPR) operator

-The Ray Path Response operator L is estimated using extended RT equations – the equations augmented with the linearized ray-tracing equations

Extended RT Equations

$$\frac{d\mathbf{X}}{d\tau} = \mathbf{F}(\mathbf{X},[N,\frac{\partial N}{\partial t}])$$

$$\frac{d\mathbf{A}}{d\tau} = \mathbf{B}(\mathbf{X},[N,\frac{\partial N}{\partial t}])\mathbf{A} \qquad B_{ij} = \partial F_i / \partial X_j \big|_{\mathbf{X}=\mathbf{X}(\tau)}$$

$$A_{ij}\big|_{\tau=0} = \delta_{ij}, \quad i, j \in [1:8]$$

8+8x8=72 equations in the extended system

Incorporation of URP Data within GPSII

NWRA Since 1984

- **The state vector is extended with coordinates of URPs**

$$U_{extended} = \left[U^T \quad \lambda_1 \quad \phi_1 \; \dot{\lambda}_1 \quad \dot{\phi}_1 \ldots \quad \lambda_N \quad \phi_N \; \dot{\lambda}_N \quad \dot{\phi}_N\right]^T$$

- **Ray path response operator (RPR) for URP**

$$L = RPR_{with\,URP} = \begin{bmatrix} RPR_{KRP} \\ L_{URP} \end{bmatrix} \qquad L_{URP} = \begin{bmatrix} \frac{\partial Y}{\partial \lambda} \\ \frac{\partial Y}{\partial \phi} \\ \frac{\partial Y}{\partial \dot{\lambda}} \\ \frac{\partial Y}{\partial \dot{\phi}} \end{bmatrix}$$

- **Evolution equation for URPs and their covariance**

$$\lambda_{t+1} = \lambda_t + \dot{\lambda}_t \Delta t + \eta_\lambda$$
$$\dot{\lambda}_{t+1} = \dot{\lambda}_t + \eta_{\dot{\lambda}}$$
$$\phi_{t+1} = \phi_t + \dot{\phi}_t \Delta t + \eta_\phi$$
$$\dot{\phi}_{t+1} = \dot{\phi}_t + \eta_{\dot{\phi}}$$

$$\overline{C}_{t+1} = \begin{bmatrix} 1 & 0 & \Delta t & 0 \\ 0 & 1 & 0 & \Delta t \\ \Delta t & 0 & 1 & 0 \\ 0 & \Delta t & 0 & 1 \end{bmatrix} C_t \begin{bmatrix} 1 & 0 & \Delta t & 0 \\ 0 & 1 & 0 & \Delta t \\ \Delta t & 0 & 1 & 0 \\ 0 & \Delta t & 0 & 1 \end{bmatrix} + \Sigma$$

- **Update equations for the extended state vector**

$$U_{n+1} = U_n + P_\alpha L^T (L P_\alpha L^T + S)^{-1} (Y - M[U_n]) \qquad P_\alpha = \begin{bmatrix} P/\alpha & 0 \\ 0 & \overline{C}_t \end{bmatrix}$$

$$C_{t+1} = \overline{C}_{t+1} - \overline{C}_{t+1} L_{URP}^T (L P_\alpha L^T + S)^{-1} L_{URP} \overline{C}_{t+1}$$

Data Collection April 22, 2016

- VA ROTHR PBIQ data (IQ data from all antenna elements)
- HF Transponder in Guatemala was turned on

Transponder Detections in the OTHR Data

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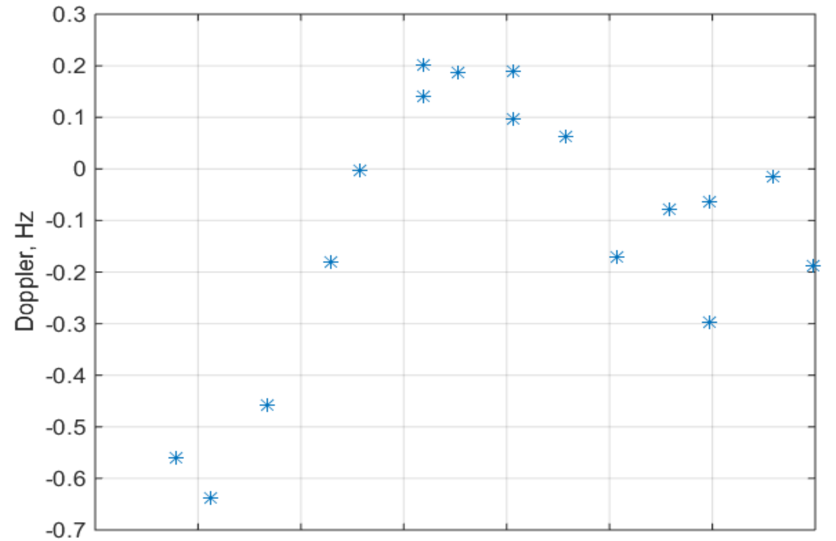
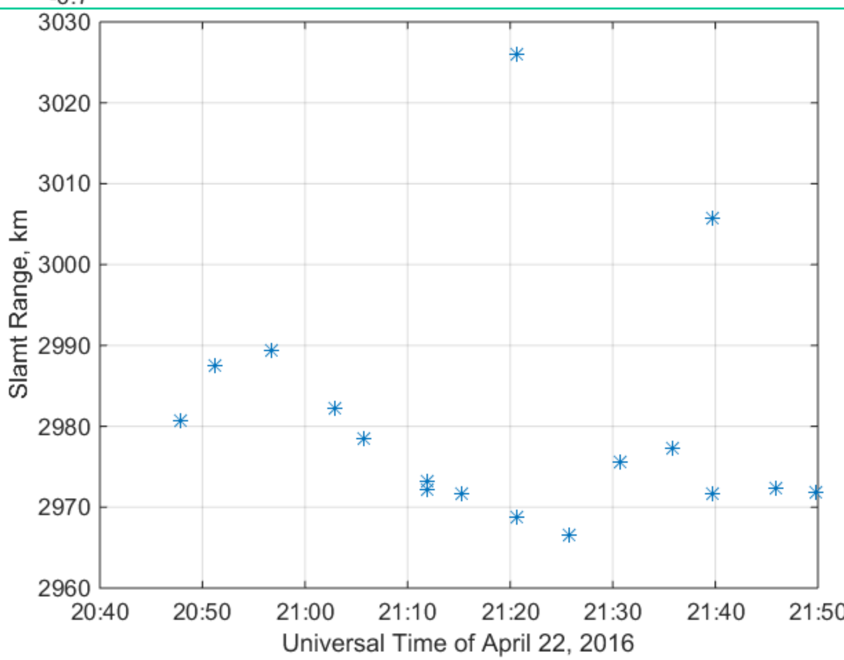
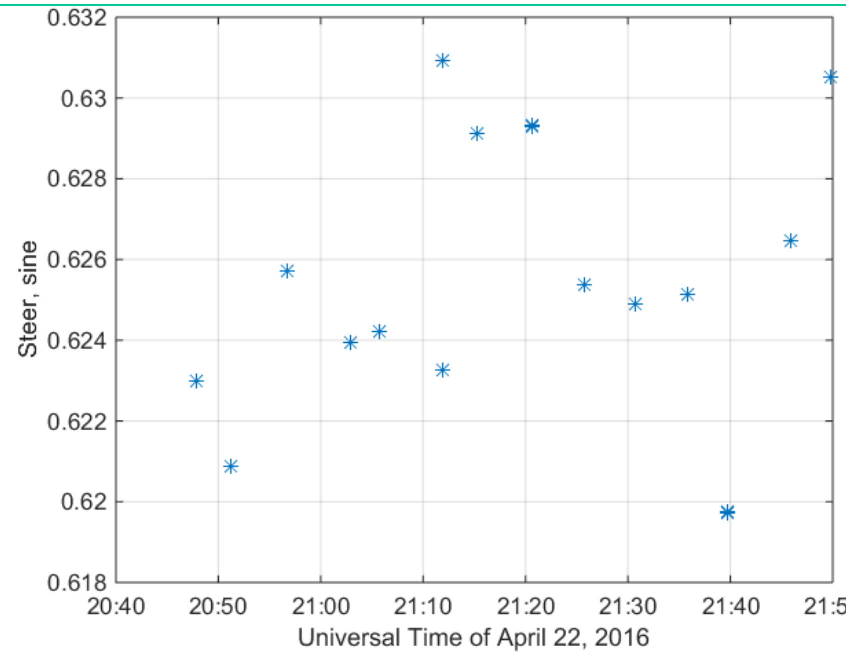


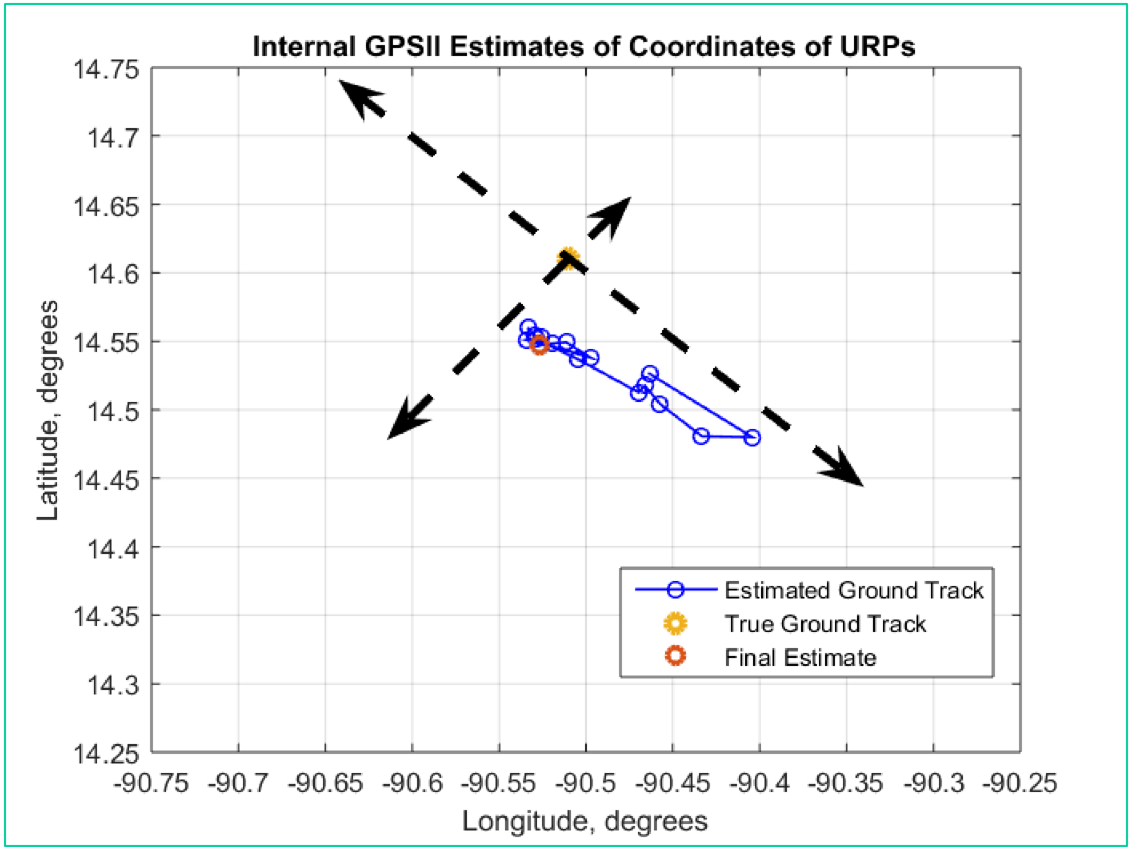
April 22, 2016





Geo-tracking within GPSII Test: Assimilation of URP data

April 22, 2016
20:47 through 21:47 UT



GPSII track (blue line)

Arrows indicate magnitude of TID-driven swings in range and azimuth if standard CR procedures have been employed

Geo-tracking within GPSII Test: Assimilation of URP data

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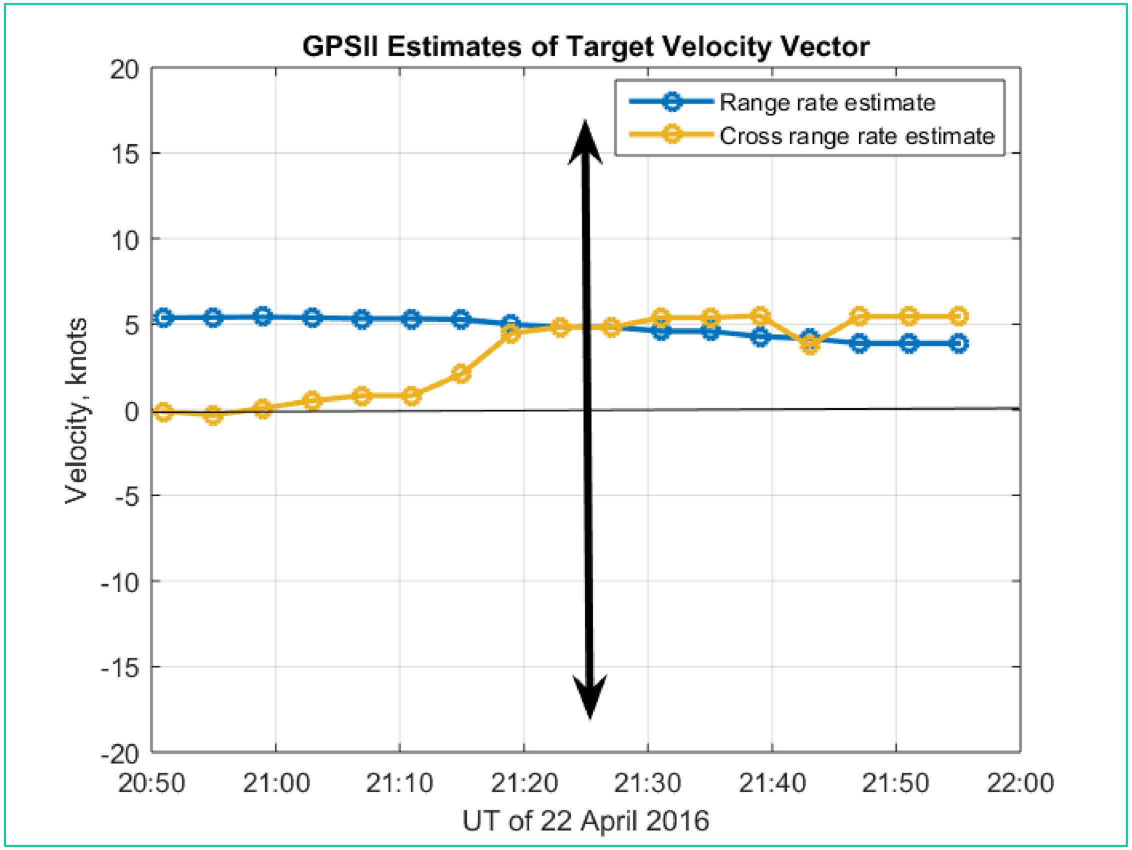
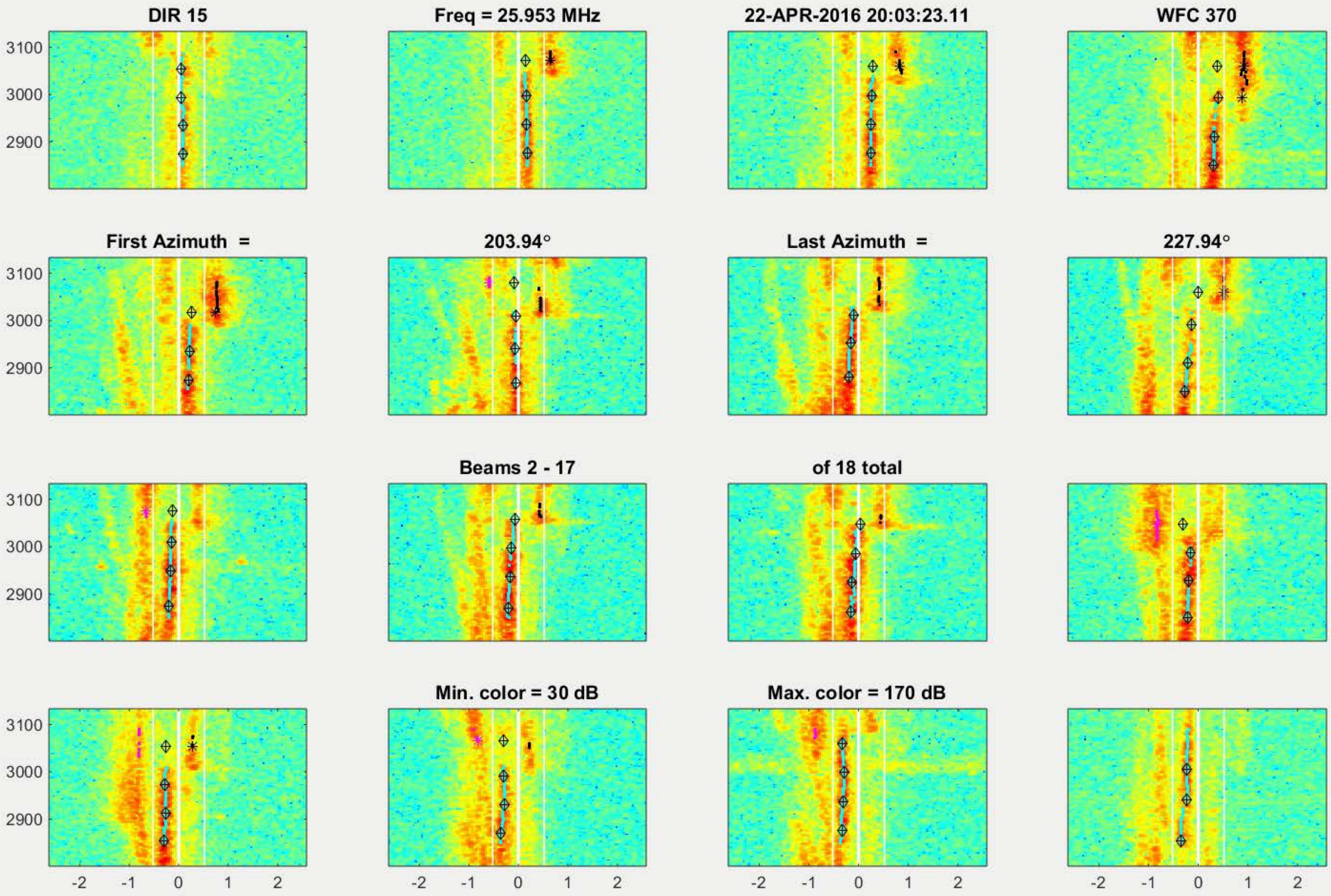


GPSII Estimates of Velocity Components
The arrow indicates magnitude of TID-driven swings in velocity components if standard CR procedures have been employed

Ground Clutter Detections as Unknown Reference Points

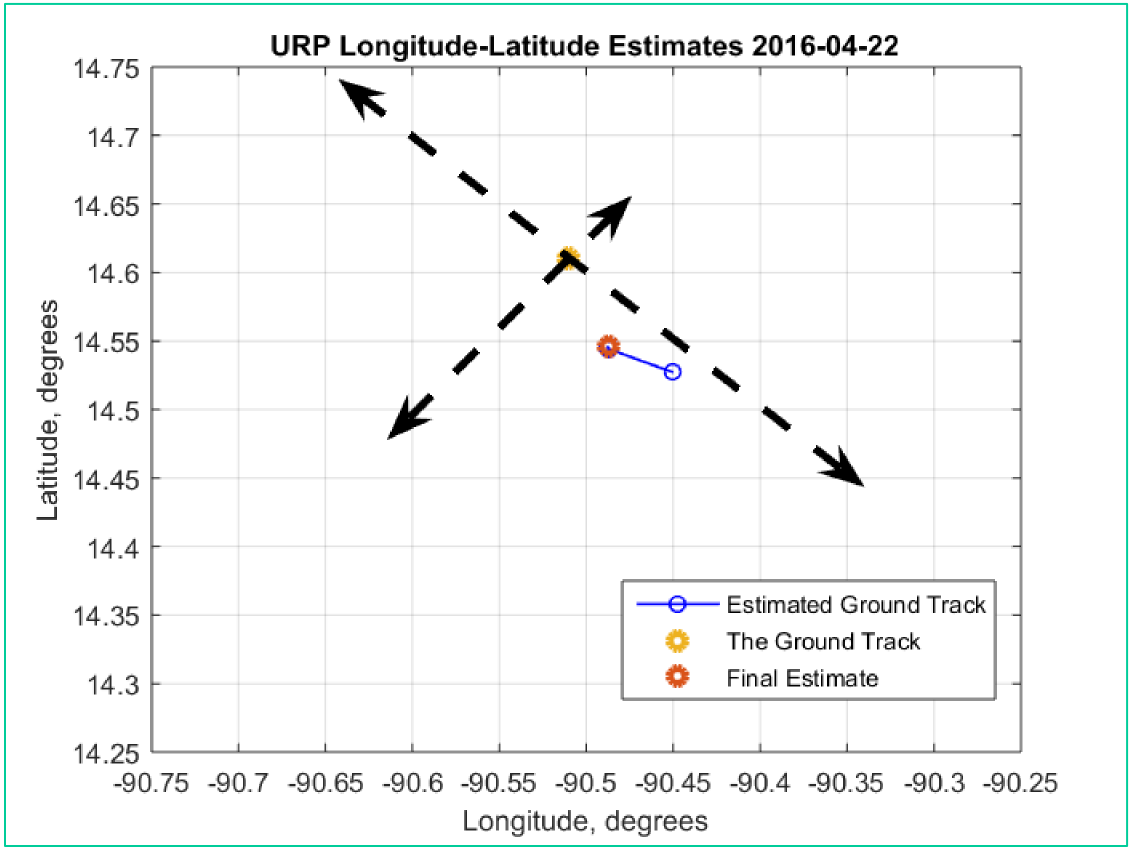


Ground Clutter Detections as Unknown Reference Points

- **Ground and ocean clutter features are easily discernable in Doppler-processed radar data**
- **The Doppler shift IDop introduced by ionospheric dynamics may be extracted from clutter detections in radar data**
  - **Time sequence of IDop data contains non-trivial information about TID structure and dynamics.**
- **Detection of surface clutter and evaluation of IDop**
  - **ridges of ground clutter are centered at IDop**
  - **ridges of ocean clutter are centered at** $\mathrm{IDop} \pm \sqrt{g/\lambda\pi}$
  - **Time series of clutter detections (slant range, steer angle, and IDop) are passed to GPSII as distinct URPs**
    - **These URPs are not tracked by GPSII**

Geo-tracking within GPSII Test: URP and IDop data

April 22, 2016
20:47 through 21:47 UT



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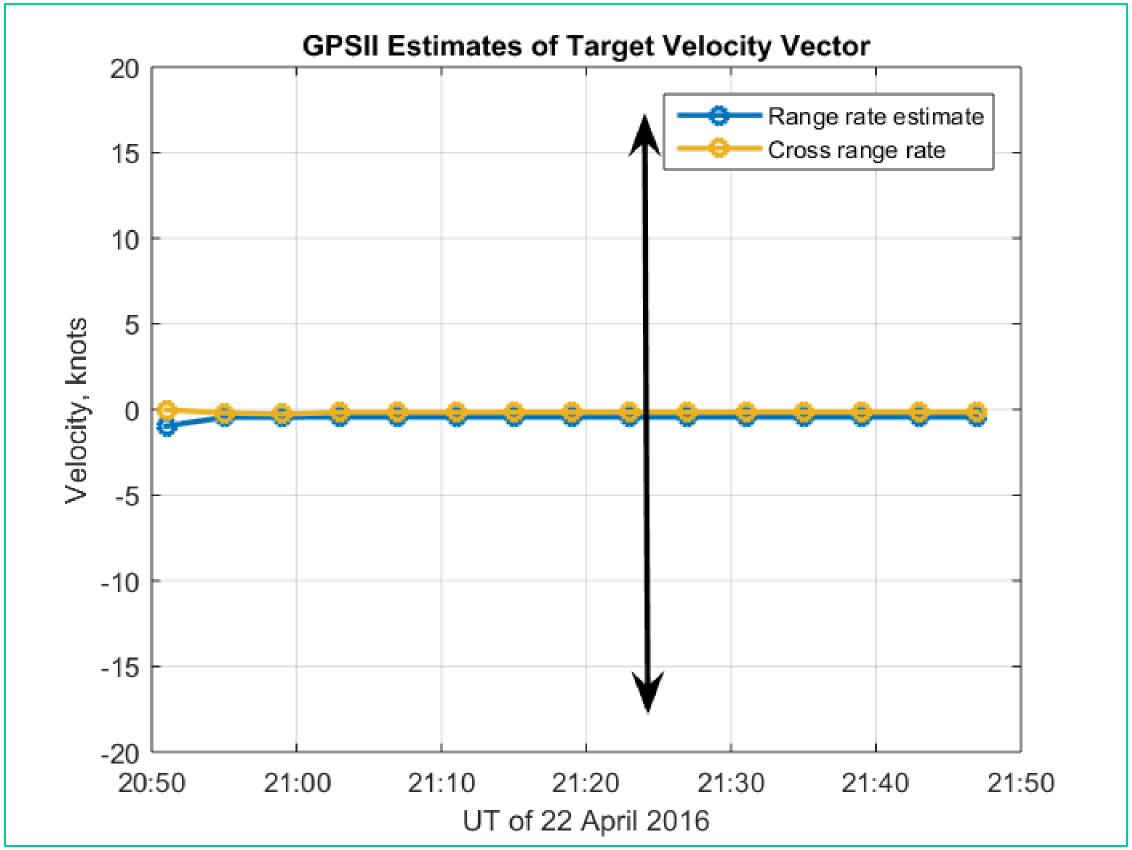

GPSII Estimates of Velocity Components

The arrow indicates magnitude of TID-driven swings in velocity components if standard CR procedures have been employed

Conclusions

- **New capability to assimilate unknown targets into GPSII ionospheric model has been introduced.**
  - **Results presented in this paper appear to demonstrate that the new capability allows mitigate effects of TIDs on OTHR geolocation.**
  - **Simultaneous assimilation of URP and IDop data provides the most impressive mitigation of transient effects from TIDs**
- **The capability to ingest and track unknown transmitters as URPs has also been introduced into the algorithm**