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

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ABSTRACT

We describe development of new HF data assimilation capabilities for our ionospheric inversion algorithm called GPSII (GPS Ionospheric Inversion). Previously existing capabilities of this algorithm (Fridman et al. 2016) included assimilation tools for data related to HF propagation channels. Measurements of propagation delay, angle-of-arrival (AoA), and the ionosphere-induced Doppler from any number of known HF propagation links can be assimilated by the model. The HF links may be established by channel probes (one way links) as well as by over-the-horizon radars (two way links). End points of such propagation links were assumed to be known. Presently we are extending the assimilative model to accommodate data from one-way and/or two-way propagation links associated with sources or radar targets with unknown locations and velocities. Time series of data from such unknown reference points (URP) has the potential to improve performance of the model in the presence traveling ionospheric disturbances. URP data from radar targets typically contain time series of AoA, propagation delay, and Doppler measurements. URP data from unknown HF transmitters are typically represented by time series of AoA measurements. In order to utilize the URP data we extended GPSII algorithm with the capability to perform Kalman filter estimation of geographical coordinates and velocity vectors of unknown targets. Thus, the algorithm simultaneously estimates the state of the ionosphere and the coordinates of URPs. We demonstrate operation of the new algorithm using time series of transponder returns collected by an over the horizon radar. The transponders are treated as unknown targets, so that GPSII geolocation of the targets can be compared to the truth. We observe that assimilation of URP data helps to substantially mitigate adverse effects of traveling ionospheric disturbances on estimation of target position and velocity.

1. INTRODUCTION

Real time ionospheric modelling proved to be of considerable importance for geolocation tasks involving skywave signals from HF sources (McNamara 1991). In this paper we describe recent progress in our effort on ionospheric modelling for HF over the horizon radar (OTHR). This is continued development of NWRA assimilative model of the ionosphere called GPSII (Fridman et al. 2016). The fundamental difference of the present approach with earlier work in the field of ionospheric modelling for OTHR geolocation (Fridman, Nickisch, and Hausman 2012) is the capability to assimilate OTHR detections of unknown targets and scatterers into the ionospheric model. Such assimilated unknown targets are called unknown reference points (URP) as opposed to known reference points (KRP) which represent radar detections associated with targets with known geographical position. Thus we are creating an algorithm that simultaneously estimates the ionospheric propagation model and target ground tracks in a way that the derived URP tracks and the propagation medium remain mutually consistent. This concept of simultaneous tracking of unknown targets and the propagation channel was originally suggested in (L. Li and J. L. Krolik 2014) for a different system.

2. INCORPORATION OF UNKNOWN REFERENCE POINTS INTO GPSII ALGORITHM

In order to accommodate URP data, the state vector of GPSII solution is extended with coordinates and velocities of URPs

$$U_{extended} = \begin{bmatrix} U^T & \lambda_1 & \phi_1 \dot{\lambda}_1 & \dot{\phi}_1 \ldots & \lambda_N & \phi_N \dot{\lambda}_N & \dot{\phi}_N \end{bmatrix}^T \qquad \textbf{(1)}$$

where λ_i, ϕ_i are geographic latitude and longitude of the URP number *i*, and $\dot{\lambda}_i, \dot{\phi}_i$ are rates of change of latitude and longitude. Assuming, for simplicity that there is only one URP, the matrix of the ray path response operator *L* is extended with the block

$$L_{URP} = \begin{bmatrix} \frac{\partial m}{\partial \lambda} & \frac{\partial m}{\partial \phi} & \frac{\partial m}{\partial \dot{\lambda}} & \frac{\partial m}{\partial \dot{\phi}} \end{bmatrix} \qquad \textbf{(2)}$$

where *m* is the column-vector of measurements (such as slant range, Doppler, steer) related to the URP. The GPSII evolution equation needs to be augmented with the evolution equation for URP positions, which we formulate as follows

$$\begin{aligned} \lambda_{t+1} &= \lambda_t + \dot{\lambda}_t \Delta t + \eta_\lambda \\ \dot{\lambda}_{t+1} &= \dot{\lambda}_t + \eta_{\dot{\lambda}} \\ \phi_{t+1} &= \phi_t + \dot{\phi}_t \Delta t + \eta_\phi \\ \dot{\phi}_{t+1} &= \dot{\phi}_t + \eta_{\dot{\phi}} \end{aligned} \qquad \textbf{(3)}$$

where Δt is the time step of the GPSII solution and η_λ, $\eta_{\dot{\lambda}}$, η_ϕ, $\eta_{\dot{\phi}}$ formally indicate the presence of Gaussian noise terms in the evolution equation. The covariance matrix of the extended state vector (1) is postulated in the form

$$P_\alpha = \begin{bmatrix} P/\alpha & 0 \\ 0 & \overline{C}_t \end{bmatrix} \qquad \textbf{(4)}$$

where *P* is the pseudo-covariance matrix of the Tikhonov method, α is the regularization parameter, and $\overline{C}_t$ is the covariance matrix of the URP component of the state vector.

The updated solution of the non-linear problem is found iteratively:

$$U^{n+1} = U^n + P_\alpha L^T (LP_\alpha L^T + S)^{-1}(Y - M[U^n]) \qquad \textbf{(5)}$$

Here Y is the vector of measurements collected between t and t+1 (this vector includes URP data), S is the covariance matrix of errors of measurements, M is the non-linear operator of measurements, L is the linearization of the operator M, index variable n numbers the non-linear iteration and it should not be confused with t. The *a posteriori* estimate of the covariance matrix of URP coordinates is given by

$$C_{t+1} = \overline{C}_{t+1} - \overline{C}_{t+1} L_{URP}^T (LP_\alpha L^T + S)^{-1} L_{URP} \overline{C}_{t+1} \qquad \textbf{(6)}$$

where the *a priori* covariance matrix of the evolved solution is estimated as

$$\overline{C}_{t+1} = \begin{bmatrix} 1 & 0 & \Delta t & 0 \\ 0 & 1 & 0 & \Delta t \\ \Delta t & 0 & 1 & 0 \\ 0 & \Delta t & 0 & 1 \end{bmatrix} C_t \begin{bmatrix} 1 & 0 & \Delta t & 0 \\ 0 & 1 & 0 & \Delta t \\ \Delta t & 0 & 1 & 0 \\ 0 & \Delta t & 0 & 1 \end{bmatrix} + \Sigma \qquad \textbf{(7)}$$

Here Σ is the covariance matrix of noise terms in (3). Thus, our solution recipe combines Tikhonov regularization with Kalman filter-based (Kalman 1960)

estimation of URP coordinates.

3. SIMULTANEOUS ASSIMILATION AND TRACKING OF UNKNOWN REFERENCE POINTS IN GPSII

Previously GPSII was able to assimilate radar return data from KRPs, that is, returns from targets at known locations. The apparent wander of these targets provides GPSII with information on what TIDs are doing to the signal returns, and GPSII can effectively use this data to model the TID structure in its 3D ionosphere model. The idea with URP assimilation is that, even though GPSII does not know the location of the source of the returns, it can use the temporal behavior of the returned delay, steer, and Doppler to try to stabilize the target, thereby attributing much of the wander to ionospheric TID activity.

We will demonstrate operation of the new algorithm using data collected by the OTHR in Virginia. Namely we will use detections of a known transponder in Guatemala. Figure 1 shows time series of Doppler, slant range, and steer data attributed to this target. Observed variations of the radar parameters of the target are mostly driven by TIDs disturbing the ray path

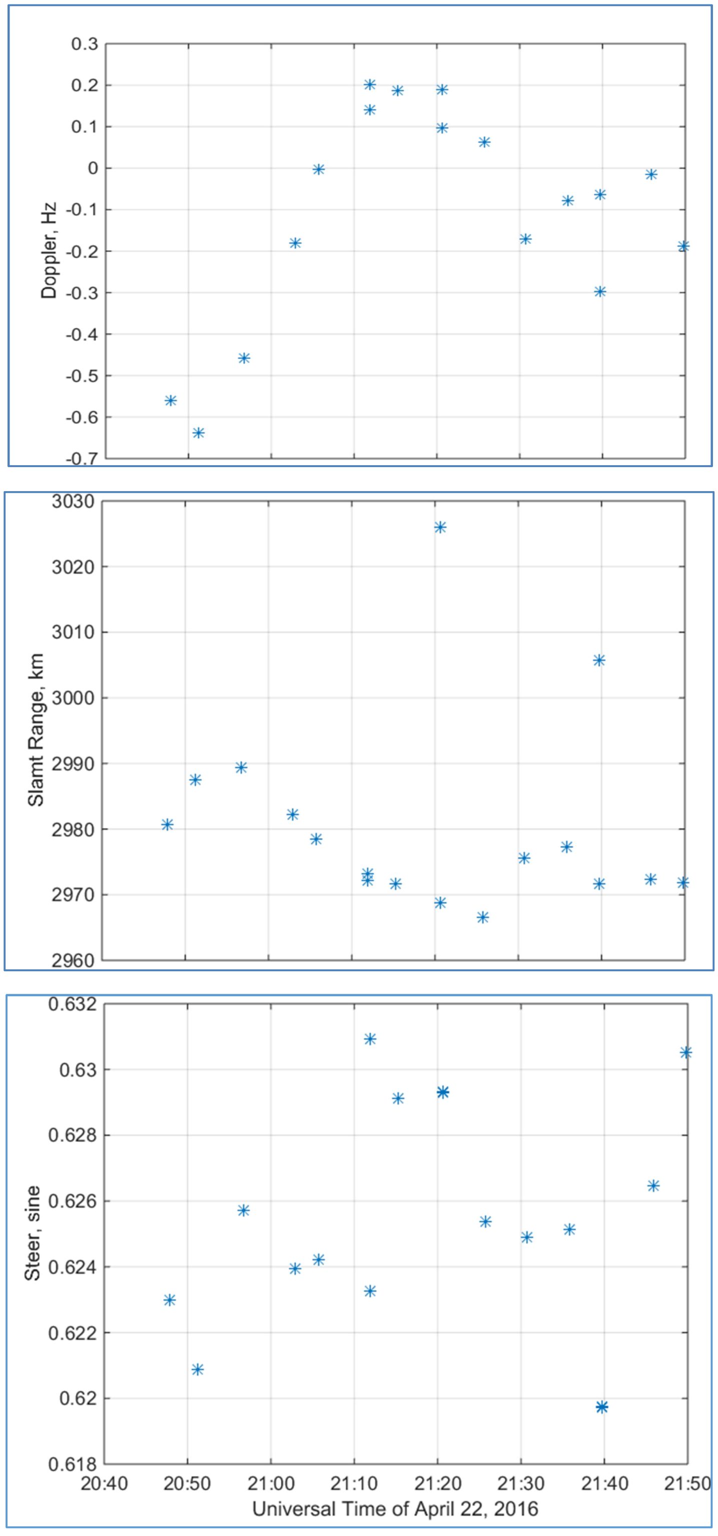

Figure 1. Detections of Guatemala transponder.

Figure 2 shows the URP-component of obtained GPSII solution when the solution was driven only by the URP data shown in Figure 1. The left plot shows the sequence of GPSII geolocation estimates. The geolocation errors appear quite small in comparison with swings in range and cross-range (black arrows) that are expected if straightforward geolocation procedures were applied.

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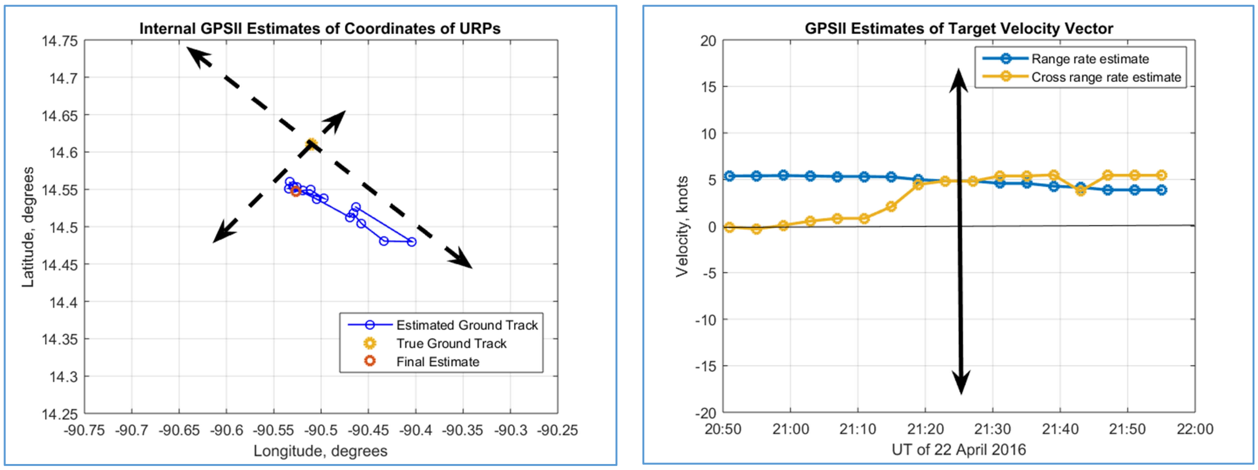

Figure 2. Sequence of GPSII estimates for target position compared to actual position of the target (at intersection of arrows in the left plot). Arrows indicate magnitude of TID-driven swings in range and azimuth if straightforward geolocation procedures have been employed. The plot on the right shows GPSII estimates of velocity components. The arrow indicates magnitude of TID-driven swings in velocity components if straightforward geolocation procedures have been employed. The true velocity of the target is zero.

4. ASSIMILATION OF GROUND CLUTTER DETECTIONS AS UNKNOWN REFERENCE POINTS

Ground and ocean clutter features are easily discernable in radar data after Doppler processing. The Doppler shift IDop introduced by ionospheric dynamics may be extracted from clutter detections in radar data (L. J. Nickisch, M. A. Hausman, and S. Fridman 2006, 2007). Time sequence of IDop data contains non-trivial information about TID structure and dynamics. Such clutter detections can be assimilated by GPSII as URPs. URP tracking process is disabled for this kind of assimilated data.

Figure 3 illustrates clutter detection processing of a single scan (dwell) of OTHR data. A set of IDop samples is produced as a result of this processing. Each IDop sample contains three scalar components (slant range, steer, and Doppler).

Figure 4 shows results URP geolocation by GPSII. One can see that TID-related swings in geolocation have been practically eliminated. Accuracy of estimating the velocity vector of the target has improved considerably.

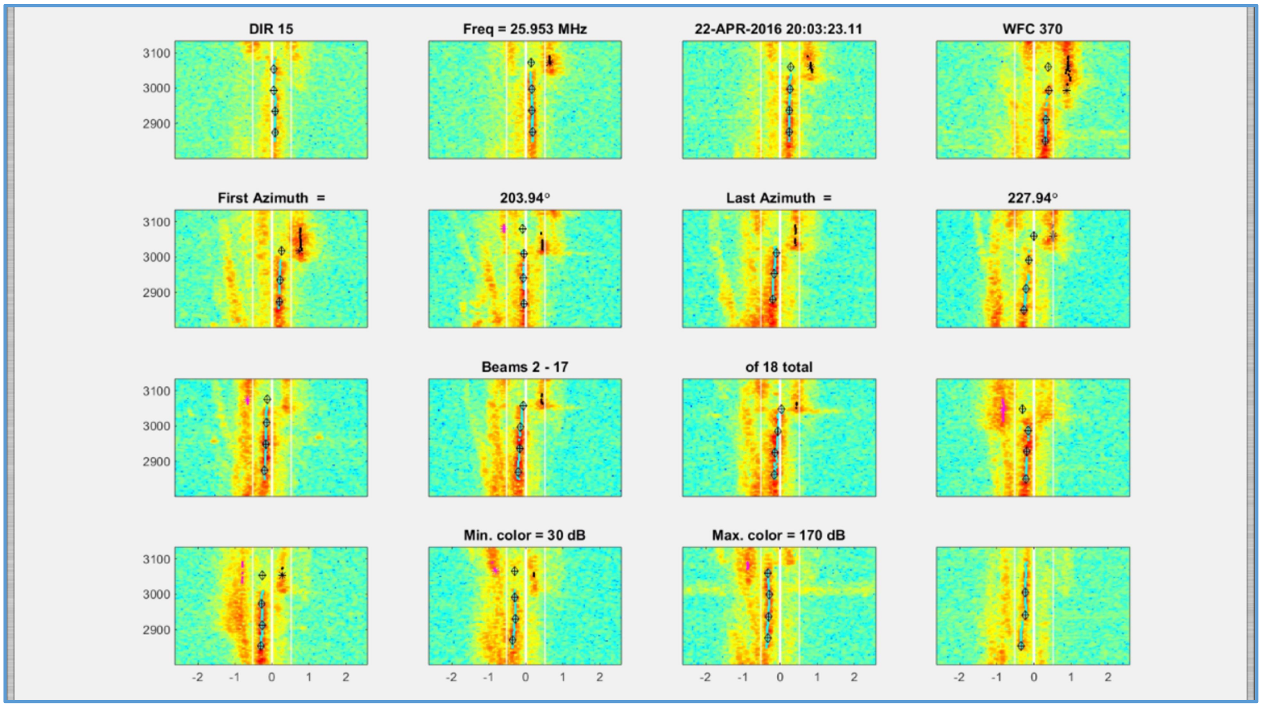

Figure 3. **Illustration of surface clutter detection in OTHR data. Each plate shows power density as a function of slant range and Doppler at a constant radar steer. Cyan pixels are located at points belonging to the crest of an apparent ridge of ground clutter. Black pixels are points classified as the crest of a positive Bragg line. Magenta pixels are points classified as the crest of a negative Bragg line. Black rhombi show the set of IDop samples passed to GPSII from this dwell. White vertical lines show position of clutter ridges in the absence of ionospheric motion.**

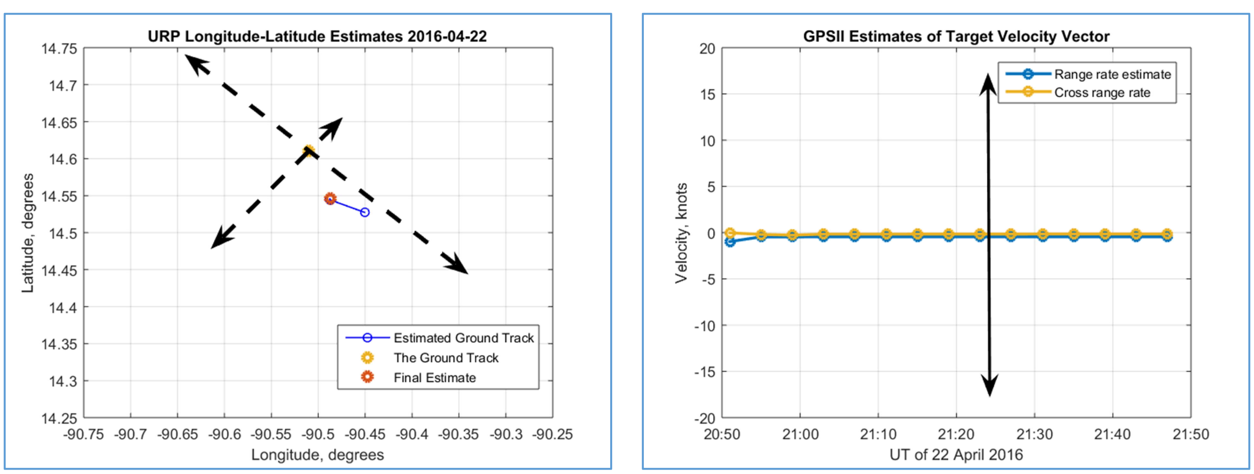

Figure 4. **Same as Figure 2 but after assimilating both IDop and URP data. Introduction of the IDop data helps to substantially reduce the TID-related swings**

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.

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