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Interactive Comment

Interactive comment on "Ionospheric assimilation of radio occultation and ground-based GPS data using non-stationary background model error covariance" *by* C. Y. Lin et al.

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Dear Editor and Referee1,

We would like to thank you for your comments on the manuscript entitled "Ionospheric assimilation of radio occultation and ground-based GPS data using non-stationary background model error covariance". However, there are many misunderstandings that we would like to clarify. Our responses to your comments are as follows:

Comment 1:

“The paper lacks for enough new information to justify its publication. It is basically the modification of an already developed and published algorithm, to deal with a new type of observations (i.e. electron densities derived from ionospheric radio occultation, instead of slant total electron content derived from ground-based GPS).”

Response 1:

The paper goal is to construct a new ionospheric data assimilation approach employing the non-stationary background model error covariance. According to the authors' knowledge, our approach has not yet been implemented in past studies. We wish to have our new technique to be published in the Atmospheric Measurement Techniques journal, and believe that the comment *“The paper lacks for enough new information”* is not justified. Moreover, we assimilate both types of slant TEC data obtained ground-based GPS and F3/C RO measurements into the IRI model. Note that the assimilation of **F3/C RO electron density profile** data is not considered in the paper. The profile data are used only for comparison and shown in Section 6. To make this point clearer in the main text, we modified the term TEC data to slant TEC data in main text.

Original (Page 2633, Line: 6): “assimilate two different types of total electron content (TEC) observations from ground-based”

Updated: “assimilate two different types of **slant** total electron content (TEC) observations from ground-based”

Original (Page 2633, Line: 15): “that assimilation of TEC data facilitated by the location-dependent background model”

Updated: “that assimilation of **slant** TEC data facilitated by the location-dependent background model”

Original (Page 2634, Line: 26): “from ground-based GPS TEC data.”

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Updated: “from ground-based GPS **slant** TEC data.”

Original (Page 2636, Line: 7-8): “The overarching goal of our study is to assimilate not only the ground-based GPS data, but also F3/C RO data into US-TEC.”

Updated: “The overarching goal of our study is to assimilate not only the ground-based GPS **slant TEC** data, but also F3/C RO **slant TEC** data into US-TEC.”

Original (Page 2636, Line: 9): “for assimilation of slant TEC between ground-based stations and GPS satellites,”

Updated: “for assimilation of **slant** TEC between ground-based stations and GPS satellites,”

Original (Page 2636, Line: 10): “ideal for assimilation of the RO TEC data.”

Updated: “ideal for assimilation of the RO **slant** TEC data.”

Original (Page 2637, Line: 8): “200 ground-based GPS stations on the CONUS and F3/C RO TEC are used in examples”

Updated: “200 ground-based GPS stations on the CONUS and F3/C RO **slant** TEC are used in examples”

Original (Page 2637, Line: 18): “The ground-based GPS TEC in this study is treated as”

Updated: “The ground-based GPS **slant** TEC in this study is treated as”

Original (Page 2643, Line: 13): “Two different kinds of TEC data are considered in the OSSEs: ground-based”

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Updated: “Two different kinds of **slant** TEC data are considered in the OSSEs: ground-based”

Original (Page 2643, Line: 16): “ground-based GPS station (black point) and F3/C occultation TEC path (red line).”

Updated: “ground-based GPS station (black point) and F3/C **RO slant** TEC path (red line).”

Original (Page 2644, Line: 18): “ground-based GPS and F3/C RO TEC data on 21 Oct 2008.”

Updated: “ground-based GPS and F3/C RO **slant** TEC data on 21 Oct 2008.”

Original (Page 2646, Line: 22): “assimilating the ground-based GPS TEC.”

Updated: “assimilating the ground-based GPS **slant** TEC.”

Original (Page 2646, Line: 23): “the ground-based GPS TEC data tend to contain”

Updated: “the ground-based GPS **slant** TEC data tend to contain”

Original (Page 2646, Line: 26): “rather irrelevant in inverting the ground-based GPS TEC data since they are a nearly.”

Updated: “rather irrelevant in inverting the ground-based GPS **slant** TEC data since they are a nearly”

Original (Page 2647, Line: 3): “RO TEC values are computed from radio signals transmitted from GPS satellites”

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Updated: "RO **slant** TEC values are computed from radio signals transmitted from GPS satellites"

Original (Page 2647, Line: 6): "To invert RO TEC data accurately,"

Updated: "To invert RO **slant** TEC data accurately,"

Original (Page 2648, Line: 4): "GPS and F3/C RO TEC agree better with the ISR electron density profile in the F region"

Updated: "GPS and F3/C RO **slant** TEC agree better with the ISR electron density profile in the F region"

Original (Page 2649, Line: 24): "GPS and F3/C RO TEC data independently,"

Updated: "GPS and F3/C RO **slant** TEC data independently,"

Original (Page 2650, Line: 6): "assimilating F3/C RO TEC does not agree well with the simulation truth."

Updated: "assimilating F3/C RO **slant** TEC does not agree well with the simulation truth."

Original (Page 2657, Fig.3.): "The F3/C RO TEC paths of assimilated observations are shown as the red line,"

Updated: "The F3/C RO **slant** TEC paths of assimilated observations are shown as the red line,"

Original (Page 2657, Fig.3.): "Note: The plus symbols indicate altitudes where TEC paths pass though this validation location,"

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Updated: “Note: The plus symbols indicate altitudes where **slant** TEC paths pass though this validation location,”

Comment 2:

“The algorithm is based on a Kalman filter, but the paper only explores the update stage of the filter, but not the forecast stage. Therefore, the filter is used to estimate a set of model parameters (i.e. the coefficients of a linear combination of empirical orthogonal functions) in order to fit, as good as possible, the measured electron densities.”

Response 2:

Our approach appears to be misunderstood here. Note that no model parameters are estimated by using the Kalman filter in this study. In this study, we implemented the Kalman filter update stage with respect to grid-point electron density values as described in Line: 7-21 in Page 2636. In other words, the 3-dimensional electron density structures are directly inferred by using the Kalman filter. The total grid number is 66,092 with the resolution of 2 degree, 2 degree, and 15km, which is the size of the state vector. The number of the covariance elements becomes over 4 billion, and so we use the empirical orthogonal functions to model the covariance to make the problem tractable. The empirical orthogonal functions and its coefficients are only used to calculate the vertical and horizontal correlation in the background model error covariance (see Section 3 Covariance models, Page 2639-2642) The Kalman filter is not used to estimate a set of model parameters.

Comment 3:

“Several works published in the last years presented different methods to solve that problem (e.g. Tsai LC, Liu CH, Hsiao TY, Huang JY (2009) A near real-time phenomenological model of ionospheric electron density based on GPS radio occultation

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data. Radio Science, Vol. 44, RS5002, doi:10.1029/2009RS004154), but the authors of the present paper do not discuss how their approach compares to other approaches described in the literature."

Response 3:

The paper's goal is to construct a new ionospheric data assimilation approach by using non-stationary background model error covariance. Therefore, the methods indicated by the referee are irrelevant. In fact, because of the misunderstanding discussed in response to Comments 1 and 2, we don't believe that our approach has much relevance to this work, which focuses on deriving an empirical ionospheric model from the F3/C RO electron density profile data. But, the Taiwan Ionospheric Model (TWIM) developed by Tsai et al., (2009) can be used in the place of the IRI model in our data assimilation study, and we mentioned it in the Discussion section in an updated manuscript.

Original (Page 2649, Line: 9): "Our data assimilation procedure has the capability to reconstruct realistic transient ionospheric features, such as plasmaspheric tails, that are absent in IRI. Resulting assimilation analyses can be used for storm time studies to identify the plasmaspheric foot points in the ionosphere."

Updated: "Our data assimilation procedure has the capability to reconstruct realistic transient ionospheric features, such as plasmaspheric tails, that are absent in IRI. Resulting assimilation analyses can be used for storm time studies to identify the plasmaspheric foot points in the ionosphere. **Moreover, the Taiwan Ionospheric Model (TWIM), which constructed from F3/C RO electron density profiles, developed by Tsai et al., (2009) can be used in the place of the IRI model in our data assimilation study to increase the accuracy of background model vertical structure.**"

Comment 4:

“The covariance matrix for the Kalman filter is not empirically estimated from the measurements, but from an ensemble of values generated with a model (i.e. the International Reference Ionosphere). Hence, this covariance can only represent the ionospheric variability at monthly median scale.”

Response 4:

In the study, the background model error covariance and observational error covariance are used in the Kalman filter update stage (See Section 3, Page 2639-2642). Since the background model is the IRI, the background model covariance needs to reflect the model error characteristics of the IRI. The background model error covariance is therefore calculated based on the ensemble of 62 IRI outputs, which are generated by perturbing model parameters (i.e. IG index and sunspot number) randomly according to a uniform distribution as described in Line 15-17 in Page 2639. The ensemble of IRI electron density distributions covers a range of the ionospheric variability. This does not mean that the variability captured by the background covariance estimated from the IRI ensemble is on the monthly scale.

The observational error covariance is calculated based on the observational data error and the variability of observations estimated in the data thinning procedure (see section 2, Page 2637 - 2639). Both background model error covariance and observational error covariance play an important role in the Kalman filter, and the paper has given extensive consideration to the estimation of both.

Comment 5:

“The results obtained with the method are validated with measurements provided by the Millstone Hill incoherent scatter radar, but only for a short period of time. This validation shows that the results worsen when the measurements used to estimate the model parameters are far from the radar location. This reveals some problems in

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the model approach (may be the covariance function), but these problems cannot be studied with only one day of measurements."

Response 5:

Again, perhaps our results may be misinterpreted here. Again, we do not use the Kalman filter to estimate a set of model parameters; we solved the Kalman filter equations with respect to the 3-dimentional electron density values. The IRI was used as it. The poor agreement of the IRI with ISR data has nothing to do with our data assimilation approach or our covariance model. The validation results show that DA results from assimilation of both ground-based GPS and F3/C RO slant TEC agree well with the ISR electron density profile. However, DA results agree poorly with ISR data when only ground-based GPS data are assimilated. Since the ground-based GPS data contain little information about the vertical ionospheric structure, assimilating ground-based GPS data alone will not alter the vertical structure predicted by the background model. (See Page 2647, Line: 24:29, and Page 2648, Line 1:8).

Interactive comment on Atmos. Meas. Tech. Discuss., 7, 2631, 2014.