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Discussions

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 Referee2,

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

PAPER SUMMARY: *"This paper is a study of data assimilation approaches for devel-*

oping nowcasts of ionospheric electron density. The study uses limited time periods (a single day) but several methods for assessing the role of location-dependent versus location-independent covariance. The focus is over the United States sector. Location-dependent covariance is demonstrably better, both in a simulation and in comparisons with independent data from radar. Despite its limitations, this is useful study worth publishing after substantial revision."

REVIEW SUMMARY: *"The paper adopts a methodical approach to answering the questions, despite a somewhat limited domain being analyzed (one day over the US). The main revision required of this paper is the clarification of the approach (is it really a Kalman filter?) and a fuller discussion of location dependent versus independent covariance. If a location independent covariance were used that had a broader correlation distance, would the results look different? Besides these points, the authors develop a useful algorithm and describe it well."*

SPECIFIC COMMENTS:

Comment1:

"p. 2635, Line 5 (2635/5): This set of equations is described as a Kalman Filter, but there is no covariance update. Later, it is stated that the KF forecast step is outside the scope of this study. It should be stated that in this case, strictly speaking, a KF is not being analyzed. This algorithm is closer to optimal interpolation. At the very least, this aspect of the analysis should be more clearly explained. It's not clear to me that the conclusions will not change if the corresponding KF is implemented. The authors should at least consider this point in the discussion."

Response1:

Thanks for the comment. In response to this comment, we have added the following description in the discussion section.

Original (Page 2647, Line: 20): "These detailed comparisons suggest that the choice of the background model error covariance needs to be suitable for all types of GPS data being assimilated; otherwise the accuracy of data assimilation analysis would not be optimal."

Updated: "These detailed comparisons suggest that the choice of the background model error covariance needs to be suitable for all types of GPS data being assimilated; otherwise the accuracy of data assimilation analysis would not be optimal.

It should be noted that the current study has not considered the KF forecast step, so our approach is closer to the optimal interpolation for the moment. In the KF, the background model error covariance is expected to evolve and become more realistic over time though a recursive application of update and forecast steps in theory. In reality, it is difficult to fully incorporate nonlinear ionospheric dynamics into the KF forecast step. The model dynamics is often simplified, and the evolution of background (forecast) model error covariance is therefore approximated. The current study represents a low-dimensional modeling of the background model error covariance, which can facilitate the future implementation of the KF in the global domain. This point will be demonstrated in our future work."

Comment2:

"p. 2638/4: Error in the pseudorange is not simply due to satellites. Ground receiver error sources are dominant such as thermal noise and multipath. Please re-state."

Response2:

Thanks for the comment. The following remark has been added in the updated manuscript.

Original (Page 2638, Line: 4): "Since the satellite error sources influence the precision of TEC calculated from pseudorange (TEC$_P$),"

Updated: "Since the satellite **and ground-based receivers** error sources influence the precision of TEC calculated from pseudorange (TEC$_P$),"

Comment3:

"p. 2638/10: This error formula applies to unbiased and uncorrelated errors, ignoring potentially significant errors due to multipath affecting pseudorange. It leads to overly optimistic observation errors. Authors should point this out."

Response3:

This error formula only calculates the error of leveling from TEC$_L$ to TEC$_P$. The F3/C RO observation data we used in the study are podTec data, and therefore the multipath error and differential code bias have been eliminated during the data processing at the CDAAC (Yue et al., 2011). The effect of differential code bias is also eliminated from the ground-based GPS data. The rms errors of the multipath effect for ground-based GPS station at elevation angles of 20° or more are typically less than 1 mm (Bevis et al., 1992) so the cutoff elevation angle of the GPS satellites is set as 20° in this study. The description of multipath effect for the ground-based receiver has been added in the updated manuscript.

Original (Page 2637, Line: 18): "The ground-based GPS TEC in this study is treated as DCB-free TEC after these DCB calibration processes."

Updated: "The ground-based GPS TEC in this study is treated as DCB-free TEC after these DCB calibration processes. **The rms errors of the multipath effect for ground-based GPS station at elevation angles of 20° or more are typically less than 1 mm (Bevis et al., 1992) so the cutoff elevation angle of the GPS satellites is set as 20° in this study.**

Comment4:

"p. 2638/18: Please mention the data rate here."

Response4:

Thanks for the comment. The original data rate of ground-based GPS and F3/C RO are 30 sec and 1 sec. After data thinning, the data rate of ground-based GPS and F3/C RO are 15.5 minute and 31 sec. The following description has been added in the updated manuscript.

Original (Page 2638, Line: 18): "To thin the data, one out of 31 continuous observation data points for a given GPS arc is selected for ingestion into the assimilation model."

Updated: "To thin the data, one out of 31 continuous observation data points for a given GPS arc is selected for ingestion into the assimilation model. **The original data rate of ground-based GPS and F3/C RO are 30 s and 1 s, respectively. After data thinning, the data rate of ground-based GPS and F3/C RO are 15.5 minutes and 31 s, respectively.**"

Comment5:

"p. 2638/25: It is not correct to state the multipath error is eliminated. In particular, the formula on line 10 assumes uncorrelated pseudorange error, which is clearly not the case in the presence of multipath. Multipath remains a significant component of

the TEC leveling error. How is representativeness error addressed? This paragraph requires revision."

Response5:

As mentioned in the response to Comment 3, the F3/C RO observation data used in the study are podTec data, the multipath error have been eliminated during the data processing at the CDAAC. The multipath effect for ground-based receiver is insignificant and can be ignore. Since the multipath effects and the differential code bias were already being considered during the preprocessing of observational data, the current study has considered the leveling TEC error and representativeness error when specifying the observational error variance. These points are mentioned in the main text.

Comment6:

"p. 2639/13: State which two months are used, because seasonal effects might not be ignored."

Response6:

Our approach appears to be misunderstood here. The background model error covariance is 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. The ensemble of IRI electron density distributions covers a range of the ionospheric variability. There are no specific months associated with the ensemble of IRI outputs.

Comment7:

"p. 2640/8: is Eqn 2 the correct equation to reference here?"

Response7:

Sorry for the typo. The correct one should be equation 3. The manuscript has been updated.

Original (Page 2640, Line: 8): "62 sets, and then multiplied by the EOFs as in Eq. (2)"

Updated: "62 sets, and then multiplied by the EOFs as in Eq. (**3**)"

Comment8:

"p. 2640/10: By "sample covariance" what is meant here? Is this viewing the 62 profiles across latitude and longitude as a sample of a single distribution? Please clarify what is mean by "sample"."

Response8:

Sorry for the confusion. The symbol cov(av,avT) in Eq (4) means the covariance of vertical EOF coefficients, which is estimated using the sample covariance of EOF coefficients. The manuscript has been added in the updated manuscript.

Original (Page 2640, Line: 11): "where cov means the sample covariance,"

Updated: "where cov **denotes the covariance**,"

Comment9:

"p. 2643/10: It should be noted also that in such simulations, difference between simulation truth and background is important. That seems to have been achieved here and should be noted explicitly."

Response9:

Thanks for the suggestion. The following remark has been added in the updated manuscript.

Original (Page 2643, Line: 10): "This parameter setting makes synthetically generated observations of electron density lower than the climatological prediction by IRI in an effort to account for the tendency of IRI to overestimate the TEC during the extreme solar minimum conditions."

Updated: "This parameter setting makes synthetically generated observations of electron density lower than the climatological prediction by IRI in an effort to account for the tendency of IRI to overestimate the TEC during the extreme solar minimum conditions. **This makes the simulation truth different from the background state.**"

Comment10:

"p. 2644/11: There is a great deal of data in Figure 3 from COSMIC. Over what time period are these data accumulated? Please clarify."

Response10:

We accumulated one-hour worth of F3/C RO and ground-based GPS observational data.

Original (Page 2657, Fig.3.): "The F3/C RO TEC paths of assimilated observations are shown as the red line, the black points are the ground-based GPS stations used in the OSSE. The green dot indicates a location where electron density profiles are sampled for comparison and validation."

Updated: "The F3/C RO TEC paths of assimilated observations are shown as the red line, the black points are the ground-based GPS stations used in the OSSE. **The data**

are accumulated over one hour. The green dot indicates a location where electron density profiles are sampled for comparison and validation."

Comment11:

"p. 2645/12: There is no visible dashed line. It is suggested to use a different color for the GPS only case."

Response11:

Thanks for pointing it out. We modified the Figure. The DA electron density profiles obtained by assimilating only ground-based GPS data are now shown by green line. The updated figure has been added in the updated manuscript.

Original (Page 2660, Fig. 6.): "The red line is the DA electron density located at Millstone Hill and the red dashed line is the DA electron density assimilating only ground-based GPS data,"

Updated: "The red line is the DA electron density located at Millstone Hill and the **green** line is the DA electron density assimilating only ground-based GPS data,"

Comment12:

"p. 2645/22: How many occultations pass through the region in this time period?"

Response12:

There are only 3 F3/C RO events passed through the location of Millstone Hill ISR in this period. The 3 RO events passed through Millstone Hill were at UT1615, UT1645, and UT1745. The following sentence has been added in the updated manuscript.

Original (Page 2645, Line: 18): "The displayed incoherent scatter radar profile is the median value over 15 min. The altitude grids where F3/C RO paths…"

Updated: "The displayed incoherent scatter radar profile is the median value over 15 min. **There are three F3/C RO observation events over the region during this period.** The altitude grids where F3/C RO paths…"

Comment13:

"p. 2645/24: It's not clear the figure shows this conclusion. Most of the time, the assimilated result is similar to background. The RO/no-RO cases look pretty similar. This conclusion should be backed up by statistics, such as mean difference or standard deviation between assimilation result and ISR data."

Response13:

Thanks for the comment. The rms deviation between ISR data and DA results from assimilation of RO and ground-based GPS data is 4.06×10^4 $\#/cm^3$. The rms deviation between ISR data and DA results from assimilation of only ground-based GPS data is 4.72×10^4 $\#/cm^3$ in this period. The following remark has been added in the updated manuscript.

Original (Page 2645, Line: 22): "In these three time periods the data assimilation result agrees well with ISR electron density. When no F3/C RO data are assimilated in addition to ground-based GPS data, the agreement of DA and ISR electron density profiles is considerably poorer."

Updated: "In these three time periods the data assimilation result agrees well with ISR electron density, **the rms deviation between DA results and ISR data is 4.06×10^4 $\#/cm^3$** . When no F3/C RO data are assimilated in addition to ground-based GPS data, the agreement of DA and ISR electron density profiles is considerably poorer, **the rms deviation between DA results and ISR data is 4.72$\times$10^{4} $\#$/cm^{3}** ."

Comment14:

"p. 2646/7: There is an error in Figure 7 (%). Why not also show comparison between Abel and ISR? This should be shown also."

Response14:

Thank you very much for the comment. The typo in Figure 7 has been corrected. Since the ISR location and F3/C RO tangent point location are different (shown at Figure 7a), we validated our DA result with those two observations separately. We compare ISR electron density with our DA result exactly at the ISR location, and compare F3/C RO electron density profile with our DA result exactly along the RO tangent points. The following remark has been added in the updated manuscript.

Original (Page 2646, Line: 2): "Figure 7a displays the 3-D observing geometry of Millstone Hill ISR (blue) and F3/C RO (red), and the TEC map from the DA result is shown on the longitude- latitude plane at the bottom."

Updated: "Figure 7a displays the 3-D observing geometry of Millstone Hill ISR (blue) and F3/C RO (red), and the TEC map from the DA result is shown on the longitude-latitude plane at the bottom. **Since the ISR location and F3/C RO tangent point location are different, we validated our DA result with ISR and F3/C RO electron density separately**."

Comment15:

"p. 2647/10: It's not clear that this is a robust conclusion. The error covariance magnitudes and forms are rather different for dependent and independence cases (D and

I). Could these results be explained by the different forms of these covariances, rather their location dependence? What if the location independent covariance had a broader Gaussian? Could that significantly affect the results? This must be explored, because a broader Gaussian that is independent is more similar to the dependent case. It's not clear to this reviewer that the location aspect is key, rather than the rather peaked nature of the independent covariance, that could have a broader horizontal correlation distance if so chosen."

Response15:

Thanks for the comment. Perhaps there may be some misunderstanding. The length scale of localization for the horizontal correlation in the location-dependent covariance is the same as the length scale of a Gaussian function used in the location-independent covariance. When the location-independent covariance had a broader Gaussian, the model error would be greater. It affects the Kalman gain to weight more the observation than the model. If the location-independent covariance were given a broader Gaussian, it would lead to the negative updated electron density value. The optimal length scale for the location-independent covariance was selected from our own trial and error and earlier US-TEC work. The correlation length scales vary over space and time in the ionosphere, which need to be reflected in the covariance model employed in the data assimilation procedure.

Comment16:

"p. 2647/29: See earlier comments on Figure 3 and how accuracy differs for the different assimilation cases."

Response16:

We accumulated F3/C RO and ground-based GPS observational data over 15 minutes for each assimilation window for "Validation with ISR data". There are only three

RO observation events that passed through the Millstone Hill location, at UT1615, UT1645, and UT1745. The rms deviation between DA results, which assimilated RO and ground-based GPS data, and ISR is $4.06\times10^{4}\#/\mathrm{cm}^{3}$ in these periods. The rms deviation between DA results, which assimilated only ground-based GPS data, and ISR is $4.72\times10^{4}\#/\mathrm{cm}^{3}$. The following remark has been added to the updated manuscript.

Original (Page 2647, Line: 26): "Both ground-based GPS and F3/C observations are located closed to the ISR at three intervals: UT1615, UT1645, and UT1745. At other time intervals, only ground-based GPS data are available. DA results agree poorly with ISR data when only ground-based GPS data are assimilated."

Updated: "Both ground-based GPS and F3/C observations are located closed to the ISR at three intervals: UT1615, UT1645, and UT1745. **In these three time periods, the rms deviation between ISR data and DA results obtained from assimilation of RO and ground-based GPS data is 4.06**$\times$**10**$^{4}\#$**/cm**^{3} . At other time intervals, only ground-based GPS data are available. DA results agree poorly with ISR data when only ground-based GPS data are assimilated. **The rms deviation between ISR data and DA results obtained from assimilation of only ground-based GPS data is 4.72**$\times$**10**$^{4}\#$**/cm**^{3} ."

Reference

Yue, X., Schreiner, W. S., Hunt, D. C., Rocken, C., and Kuo, Y. H., Quantitative evaluation of the low Earth orbit satellite based slant total electron content determination, Space Weather, 9, S09001, doi:10.1029/2011SW000687, 2011.

Bevis, M., Businger, S., Herring, T., Rocken, C., Anthes, R., and Ware, R., GPS meteorology: Remote sensing of atmospheric water vapor using the Global Positioning System, J. Geophys. Res., 97, 15787-15801, 1992."

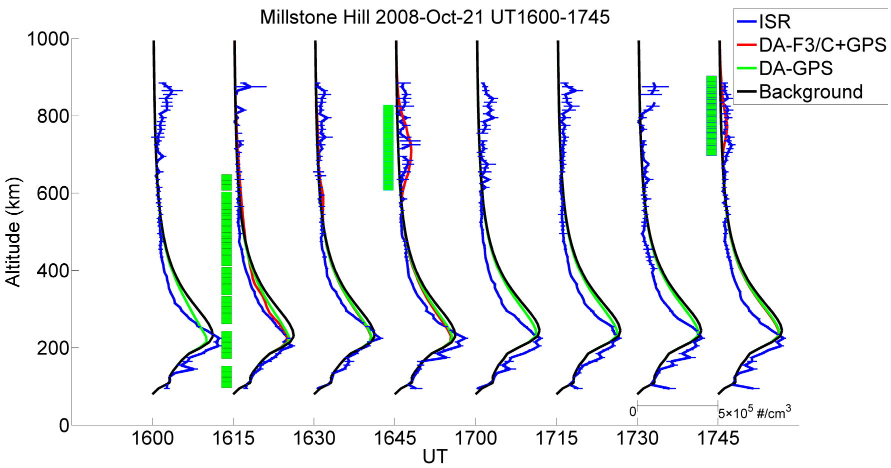

Fig. 1. Updated Figure 6

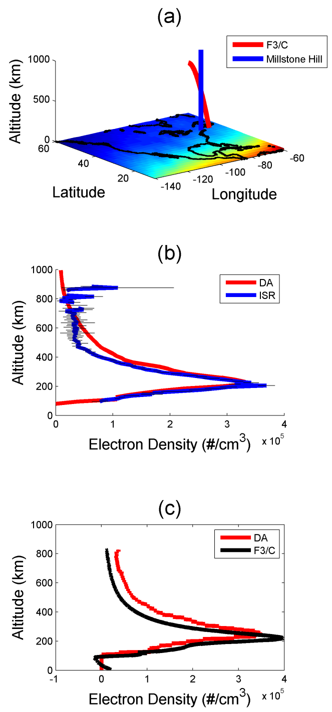

Fig. 2. Updated Figure 7