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Interactive Comment

Interactive comment on "Ionosonde measurements in Bayesian statistical ionospheric tomography with incoherent scatter radar validation" *by* J. Norberg et al.

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Authors would like to thank the associate editor and anonymous referees for giving valuable comments on the manuscript. The authors have taken into account the comments and the corresponding responses are given here after each comment.

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1 Reviewer #1 (Comments to Author):

General comments

The submitted paper represents a significant contribution to the field of ionospheric tomography. A key point in ionospheric tomography is how vertical information is obtained. This work uses ionosonde measurements for this purpose, and interprets these data in the form of a prior distribution to be used in a Bayesian inversion. Of course, the problem is still underdetermined, and other regularizing information must be used. Typically, some sort of smoothness constraint is used. In the present work, the authors use a clever techinque to quantify this smoothness in terms of correlation lengths, incorporated in the prior distribution (described in their previous paper, Norberg et al.[2015]). The technique in the submitted paper is an advance in the state of the art in combining ionosondes with radio beacons for tomography. One advantage is the use of precision matrices, which are sparse, instead of explicit covariance matrices, which allows for fast computation and real-time operation. The description of the methodology is clear, accessible, and succinct. Through experiment, the paper demonstrates the improvement gained by using this method over existing methods for choosing the prior (namely, IRI-based and zero-mean methods). The main drawback of this work (detailed below) is the seemingly arbitrary nature of choosing free parameters in the inversion. However, as the authors state, such ad-hoc techniques are endemic to any regularization techinque, and in the present work, this ad-hoc nature can be quantified in physical units, unlike other techniques. Nevertheless, the reader is left with the question of how sensitive the reconstruction is to the choice of these free parameters. This question could perhaps be answered by providing a detailed description of the truth model simulation that is hinted at in the text.

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Specific comments in order of decreasing importance:

1. p9823: The authors describe the choice of what appear to be seven free parameters in their method. For the prior mean, the measured ionosonde data is used for the bottomside, and for the topside an exponential distribution with a scale height of 140 km is used. For the prior standard deviation, the authors choose a Chapman profile, with a peak electron density of 40% of the prior mean, a scale height of 200 km above the peak and 60 km below it, and a peak altitude "approximately the same" as in the prior mean. To describe the correlation lengths in the prior, the authors use 200 km in the vertical direction and 2 degrees in the horizontal. The authors state that they exercised various combinations of the free parameters to find the values to be used in subsequent reconstructions. These values are set constant for the first three inversions, but some values are changed for the fourth inversion. It would provide a great benefit to the perceived robustness of the proposed method to describe the process of choosing these parameters, perhaps with a truth model simulation for better justification. This complexity is the weakest point of this work, which is unfortunate given the beauty and simplicity of the description in Section 2 and the construction of the prior precision matrix as described by Norberg et al (2015).

Based on the comments in both of the reviews, we decided that dividing Conclusion section to separate Discussion and Conclusions sections would help the manuscript. In Discussion we would like to elaborate on the parameter selection and robustness.

"The presented method for ionospheric tomography includes several prior parameters and the selection of the corresponding values might seem arbitrary. The objective of this article is not to optimize all of the prior parameters, but to concentrate on the altitude profiles of the prior mean and the standard deviation. Based on trials with the

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algorithm and different data, the information on the vertical structures has the most crucial effect on the reconstruction quality. This is also evident in the presented results. When zero mean prior is used, the peak altitude can be found relatively well, but the measurements do not contain enough information to produce steep enough vertical gradients. Then again, when a vertical profile is given within the prior, the reconstruction of peak electron density is improved significantly, but the peak altitude becomes less sensitive to measurements. In horizontal direction, the gradients can be reconstructed rather well regardless of the prior mean in use. Hence, information on horizontal electron density structures (IRI model) is less important if the trade off is the accuracy on the vertical structure.

When accurate vertical electron density profile is provided within the prior, the selection for the values of the other prior parameters is less critical. For all prior parameters the stabilizing effect is also rather intuitive. Decreasing the correlation lengths allow more small scale variation in the reconstructions, however, getting close to the the corresponding discretization can result in artefacts. The increment of correlation lengths smoothens the reconstruction, but very long correlation lengths can again produce unexpected behvaiour. With all cases in the previous section, the use of horizontal correlation length values between 1° and 10° and vertical correlation lengths between 20 and 500 km were carried out without drastically unrealistic changes in reconstructions. The peak value of standard deviation was also altered in a range from 20% to 100% with anticipated results.

As mentioned in section 3, the standard deviation profile is parametrized as a Chapman function. Hence, the ionosonde profile cannot be used explicitly, but the choice of the parameter values can be done viably based on the ionosonde measurements. For the three first overflights only the peak standard deviation altitude and density were set according the corresponding ionosonde measurements. With Overflight IV, the ionosonde profiles are significantly different, thus also the shape of the prior standard deviation was changed. Altogether, the results for the overflights II, III and IV could

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be enhanced by optimizing the parameters through trial and error individually for each case, but the results show that already intuitive realistic choices of these parameters are enough to give reasonable solutions."

2. The authors should cite recent work by Chiang and Psiaki (2014) and discuss the relationship with their work. K.Q.Z. Chiang and M.L. Psiaki, "GPS and Ionosonde Data Fusion for Local Ionospheric Parameterization," Proc. ION GNSS+ 2014, Sept. 9-12, 2014, Tampa, FL, pp. 1163- 1172.

We were not familiar with this paper. We would like to add in the manuscript: "Chiang and Psiaki (2014) combined ionosonde data with GPS measurements for ionospheric tomography. The presented method concentrates in estimating parametrized local electron density profile at the location of the ionosonde. For latitudinal and longitudinal changes, only the first order dependence of vertical total electron content was considered."

3. In Equation (1), is gamma (the unknown receiver bias) a multiple of 2pi, or can it be any real number? Either way, it needs to be made clear what prior is used for these parameters. If it's restricted to a multiple of 2pi, the authors need to describe how this is handled.

To the part where we introduce the prior distribution it could be added: "Again, the vector μ as well as the matrix $\mathbf{\Sigma}_{pr}$ consists of parts for both, the unknown electron densities and the unknown γ parameters." And the following sentence in the section where we state the used parameters: "For all of the experiments, the prior mean values for the γ parameters are set to zero, and the prior standard deviations as large as 10^{20} $\mathrm{Ne/m^3}$, nearing an uninformative prior."

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The prior distribution for the γ parameter could be also estimated more carefully. However, as the prior is Gaussian, it is not limited to integer multiples of 2π. The accuracy of estimated phase constants is worse than 2π, thus including this information into the model would not be significant.

4. Is a periodic boundary condition used in this work, as described in Norberg et al (2015)?

We would like to add: "For numerical reasons, the prior distribution is built to have periodic boundary conditions (Norberg et al., 2015). Here, the given vertical prior profile constrains the values of highest and lowest altitudes so strongly, that boundary effects in that direction are prevented. To avoid boundary effects in horizontal direction, the correlation lengths at the boundaries are decreased to 10% of the initial values and the actual inversion is carried out in a larger domain than is our actual interest."

5. The authors took care to mention the caveat regarding the use of the UHF data to calibrate the dynasonde measurement. However, on page 9831 line 18, it's not made clear whether the profiles used for validation in this paper were also used for calibration. Please make this clearer, as it substantially affects the interpretation of the results.

We would like to elaborate this in new Discussion section: "Electron density profiles measured with the EISCAT UHF are routinely calibrated by means of comparing F-region peak electron density estimates from the UHF and the dynasonde. Thus, when the ionosonde-based prior is used, F-region peak densities above the Tromsø site are taken from the same instrument in both the tomography prior and the UHF

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results. Our tomography measurements and the ground truth UHF measurements are thus not completely independent. However, we anticipate that this is not a very serious problem, as the calibration data were not used for the validation. Furthermore, calibration does not affect the UHF density profile shape, but only its absolute values, and calibration is not performed for individual profiles, but same scaling is used for a longer period of time. Especially, the actual validation measurements with beam steered far away from zenith are never used for calibration."

6. Please briefly describe how the measurement covariance matrix is constructed, or provide a suitable reference.

It could be added: "The chosen sampling rate of 0.5 Hz produces between 100 and 200 suitable measurements from each receiver station. The corresponding measurement errors are estimated from the original 20 Hz sampling rate data. The measurement errors are assumed to be Gaussian and independent, resulting in a diagonal measurement error covariance matrix."

7. p9830 line 17: Slightly more detail is needed regarding how negative values are handled. The method that is described seems to me like a justifiable and efficient way of enforcing a non-negativity constraint, but it is not entirely clear. Furthermore, are there any numerical issues with setting such a small variance?

We would like to elaborate further: "Unfortunately, the linear system allows also negative values in the solution. Large proportion of negative values would suggest that the prior distribution differs drastically from the actual ionospheric conditions and needs to be reconsidered. Then again, small areas of negative values indicate that the model accuracy is less than the corresponding absolute values. Here, if some

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negative values are found, we add them as new measurements into the linear system. We then set these new measurements to zero with a small variance (10^{-20}) and solve the system again. We note that here this positivity constraint is mostly a cosmetic ad hoc method which will be reconsidered in future studies."

8. For tables 1-4, how is the "true" peak altitude determined? From the ISR (in which case smoothing is needed) or from the ionosonde (in which case it may not be a fair comparison)?

In the Table 1 header it is said "Errors of tomographic profiles compared with EISCAT UHF scans" In the text it could be added: "The altitude resolution used for EISCAT data analysis was 10 km." Which gives an understanding on the smoothing and altitude accuracy.

9. p9831 line 3: It may or may not be useful to indicate to the reader how much the measured ionosonde profile varied over 10 min.

For each of the Overflight I - IV sections a sentence "The largest differences between the ionosonde profiles were at xxx km altitude, with standard deviation of x$\times 10^{11}$ $\mathrm{Ne/m^3}$ The peak altitudes range from xxx to xxx km" could be added."

These values for the different overflights in respective order are: Altitude of largest differences 330, 260, 310 and 180 km. Standard deviations at these altitudes are 2.3 $\times 10^{11}$, altitude 2.3 $\times 10^{11}$, 0.6 $\times 10^{11}$, 0.5 $\times 10^{11}$ and 0.7 $\times 10^{11}$ $\mathrm{Ne/m^3}$. The peak altitudes ranges are 320 - 340, 260 - 280, 250 - 320 and 110 - 410 km, as in Overflight IV the strong E region peak is not visible in the first ionosonde profile.

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10. p9825 line 24. This whole paragraph may benefit from a reference to where the reader may find more information about ionosondes.

Maybe a reference to Breit and Tuve (1926).

11. Higher resolution figures (especially figure 4) are necessary to be suitable for publication.

This can be done easily.

Technical corrections:

(The following corrections are minor and should be treated as recommendations only:)

A. Eq 1: Replace "dz" with "dl". Since z is a two-element vector, dz doesn't seem right.
B. p9288 line 8: Using the index "t" may be mistaken for time instead of the index of the measurement.

" $\mathrm{m}_{t,\mathsf{sat},\mathsf{rec}} = \gamma_{\mathsf{sat},\mathsf{rec}} + \int_{L_{t,\mathsf{sat},\mathsf{rec}}} N_\mathsf{e}(z)\mathrm{d}l + \varepsilon_{t,\mathsf{sat},\mathsf{rec}}$,where $m_{t,\mathsf{sat},\mathsf{rec}}$ is the measured relative total electron content at time t between the satellite sat and receiver rec, and $\varepsilon_{t,\mathsf{sat},\mathsf{rec}}$ the corresponding measurement error. $N_\mathsf{e}(z)$ is the two-dimensional continuous field of electron densities with coordinates $z := (z_1, z_2) \in \mathbb{R}^2$. The integral is defined over the measurement signal path $L_{t,\mathsf{sat},\mathsf{rec}}$. The receiver-satellite specific constant $\gamma_{\mathsf{sat},\mathsf{rec}}$ is due to the unknown amount of electron content when the satellite is first observed."

We actually define index "t" as time. Here we added indices "sat" for satellites and

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"rec" for receivers.

C. p9831 line 1: add the word "is"

"The altitude of COSMOS satellites is approximately 1000 km and the duration of measurements from an overflight is roughly 10 min."

D. p9835 lines 1 and 15 are not complete sentences.
Starting ⇒ starts. "The COSMOS 2407 overflight starting at 14 March 2015 13:20UTC (Fig. 5)."

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