

Response to Dr. Culverwell: (comments are in blue; replies are in black)

On p 7788, line 10 the authors assert that Healy and Culverwell (2015) found that, "at heights lower than the maximum by two height scales the response is well approximated by $(z_0-h)^{-3/2}$, ie is the same as those (sic) from the delta function". This is not the case. (No bending angles are shown in that paper, only the residual errors on them.) In fact, one needs to be about 15 ionospheric scale heights below the peak height before the delta function solution is even within 10% of the true bending angle, at least for the Chapman layer ionospheric model that we developed. The delta function is therefore an instructive theoretical limit, but it is of little use in practice. (Of course, if the delta function response is scaled by a coefficient that can adjusted by fitting to the data then it is not such a bad model: the shape (slowly increasing upwards) is roughly right, even if the magnitude isn't.) This is why Culverwell and Healy (2012) discussed a better model ("Z(l)") to describe the bending caused by a Chapman layer ionosphere. It is therefore stretching things a bit to say, as Zeng et al do, that the $D(z_{F2}-h)^{-3/2}$ term in Eqn 7 is "similar" to that used by C&H in 2012. Perhaps "analogous" would be more accurate?

Nor is it quite fair to say that the Z(l) of C&H 2012 is a model for extrapolating $\alpha_1 - \alpha_2$. It can be used as such, but in fact it is a model of α_1 and α_2 individually. It can be used, for instance, even if α_2 is completely absent, which $(\alpha_2 - \alpha_1)$ extrapolation techniques such as that discussed by Zeng et al clearly cannot. It does this because it contains an explicit, very simple, model of the ionosphere, whose characteristics, in an assimilation context, are recovered as part of the retrieval process - because they are part of the forward model.

(Incidentally, the 'integrated by parts' version of the Abel integral in Eqn 6 should read $[\Delta(z-z_0)/\sqrt{z-h}]_h^{\infty} + 1/2 \int_h^{\infty} \Delta(z-z_0)/(z-h)^{3/2} dz$.)

Answer: We apologize for the incorrect citation: we meant (Culverwell and Healy, 2012). In that presentation, they considered the response from delta function as one of the possible simple models for the ionospheric bending angle well below the peak height (along with other more accurate models).

It is clear that if the model is considered for direct modeling of the ionospheric effect using single frequency, then the requirements for such modeling are much higher than for the model used for extrapolation of the dual frequency ionospheric correction in the troposphere (as in our study).

Still, the statement that "one needs to be about 15 ionospheric scale heights below the peak height before the delta function solution is even within 10% of the true bending angle value" is not quite clear. Slide 6 from (Culverwell and Healy, 2012) reproduced below in Figure C1, shows that about 10% agreement between the true bending angle (green) and delta function solution (red) is achieved at about 3 scale heights below the peak.

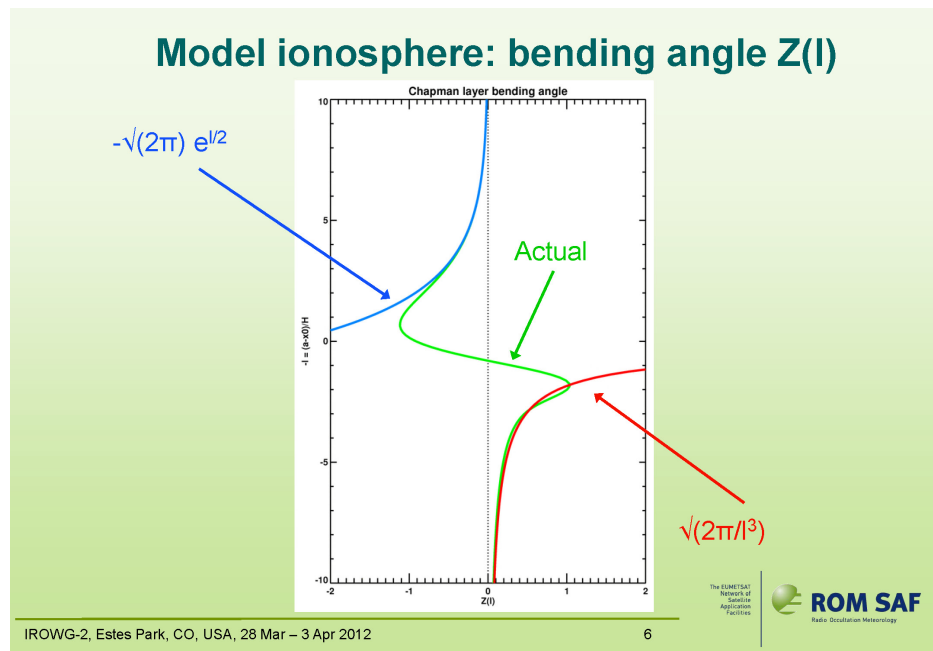


Figure C1. Culverwell, I. and Healy, S.: Ionospheric correction of RO signals by direct modeling of the ionosphere, Presentation at IROWG-2 Workshop, Estes Park, CO, USA, March 28 - April 3, Slide 6.

(<http://irowg.org/wpcms/wp-content/uploads/2013/12/culverwell.pdf>), 2012.

Results of our modeling are shown in Figure C2. Left panel shows the electron density profiles modeled by Chapman layer. Blue lines: F2 layer peaked at 300 km with vertical scale 50 km (dashed line) and 75 km (solid line). Green lines: E layer peaked at 100 km with vertical scale 5 km (dashed line) and 7.5 km (solid line). Right panel shows L1-L2 bending angles obtained by ray-tracing for the profiles given in left panel (blue and green lines) and approximations by bending angles calculated for refractivities modeled by delta-functions at 300 km and 100 km (red lines). It is seen that the fitting obtained with delta function model, at least for F2 layer, is not substantially different from that on Figure C1 (Culverwell and Healy, 2012). For the scale height 75 km, the difference between true bending angle and "delta fit" at 80 km (about 3 scale heights below F2 peak at 300 km) clearly does not exceed 10%.

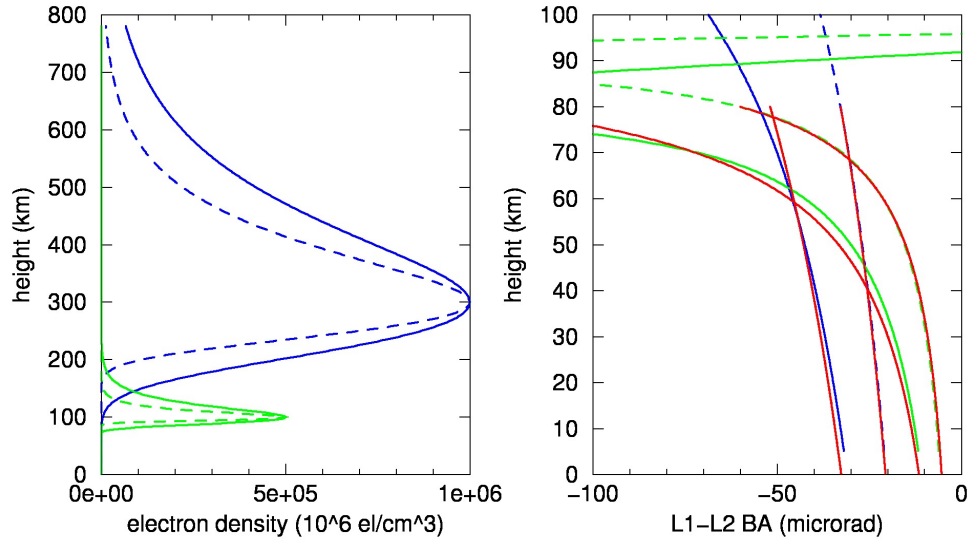


Figure C2. F-layer (blue, peak at 300 km) and E-layer (green, peak at 100 km) electron density profiles modeled by Chapman layer (left); L1-L2 bending angle profiles obtained by ray-tracing (blue and green) and approximated by the fitting functions derived from delta function ionospheric model.

We are grateful for pointing to the problem in equation (6); it is corrected in the revised paper.