Daedalus Ionospheric Profile Continuation (DIPCont): Monte Carlo Studies Assessing the Quality of In Situ Measurement Extrapolation

— 2nd Revision : Reply to Reviewer 2 —

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Second manuscript revision: Reply to Reviewer 2

The authors thank both reviewers for carefully evaluating the revised manuscript.

Below are our responses to the comments of the second reviewer.

Comments on: *Daedalus Ionospheric Profile Continuation (DIPCont): Monte Carlo Studies Assessing the Quality of In Situ Measurement Extrapolation*, by Vogt et al.

This is a revised paper with a slightly different title that presents simulated calculations including extrapolations of altitude profiles of various ionospheric state parameters that would be measured by in situ instruments on a pair of low perigee, orbiting platforms such as the proposed Daedalus mission.

Although the paper is improved, there remains one area that the authors are asked to address. After this item is addressed, the paper should be ready for publication in Geospace Instrumentation.

1. Uncertainty of geophysical conditions corresponding to Figures 1, 7, and 8

This reviewer is still perplexed by Figures 1, 7, and 8 and the relevant parameters used for the analysis involving this figure.

First, it is not until the bottom of page 18 that the reader learns that the two peaks of the density and Pedersen conductivity near 115 km at +/-1000 km corresponds to simulated auroral precipitation. The reader also learns that the horizontal distance pertains to latitude and the center is the highest latitude, presumably in the polar cap. This should all be explained when Figure 1 is introduced and reflected in the caption.

The introductory text was amended as follows.

[. . .] The basic ideas are illustrated in Figure 1, displaying electron density and Pedersen conductivity extrapolation horizons for a range of relative error thresholds along the orbits of a dual-satellite mission. Horizontal distance corresponds to the latitudinal (north-south) direction, with the origin of the horizontal axis centered at the highest latitude along the satellite orbits. In the LTI model runs leading to Figure 1, latitudinal inhomogeneity parameters are set to reproduce the two electron density maxima observed by a polar orbiting satellite when crossing the auroral oval. See Section 4 and Appendix D for details. It is important to note that the filled contour representations of electron density and Pedersen conductivity model distributions mainly serve to provide contextual information, while the essential results of the DIPCont modeling procedure are the extrapolation horizons represented as plain contour lines, [. . .]

The caption of Figure 1 was amended as follows.

Extrapolation horizons and orbit configuration displayed on top of a two-dimensional section of the modeled LTI. Upper panel: Electron density N_e. Lower panel: Pedersen conductivity σ_P. Horizontal distance corresponds to the latitudinal (north-south) direction, with the origin of the horizontal axis centered at the highest latitude along the satellite orbits. In the LTI model runs leading to this figure, latitudinal inhomogeneity parameters are set to reproduce the two electron density maxima observed by a polar orbiting satellite when crossing the auroral oval. Synthetic measurements are produced [. . .]

> The season and solar illumination used in the simulations is important for understanding the analysis particularly with respect to Figure 1, 7, 8. The reader needs to know what is the solar angle and understand the photoionization production for which the Chapman function is analyzed as part of the analysis. This should be clearly stated with respect to the parameters in Figure 1, 7, and 8.

As explained in our March 2023 response to the comments of reviewer 2, the DIPCont project is less concerned with LTI modeling but with assessing the *quality* of downward continuation of in situ measurements as reflected in probabilistic measures of deviation obtained through Monte Carlo simulations. In the March 2023 revision, major parts of the manuscript were rewritten to clarify the scope and the goals of the DIPCont project. The objective of this initial DIPCont paper is to introduce the probabilistic methodology and key concepts such as extrapolation horizons. The initial version of the DIPCont package contains a simplified description of the LTI, choosing the process of Pedersen conductivity formation as an indicative example to demonstrate the procedure and key DIPCont products. To this end, a single-species LTI model with an intentionally limited set of parameters and an incomplete representation of ionization processes is constructed.
At this stage, season and solar illumation are only implicitly represented through the set of (vertical) LTI model parameters listed in Table 1 and horizontal profile parameters that are available in the Python code as part of the supplementary material. The parameters used for the simulation runs in this initial DIPCont paper are the default parameters specified in the parameter configuration file `DIPContBas.py` as part of the supplementary material provided with this paper.
Now, as part of the second (August 2023) revision of the DIPCont paper, Appendix D is added to describe the simulation parameters and the functional form of the horizontal electron variations leading the LTI model setup in Figures 1, 7, and 8.

Appendix D: Parametrization of horizontal electron density variations

In the initial version of the DIPCont package, the horizontal variability of electron density profiles is controlled by the keyword argument `LTIModelType`. Setting `LTIModelType='NeAuroralZoneCrossing'` produces two electron density maxima along the horizontal (latitudinal) axis as observed by a polar orbiting satellite when crossing the auroral oval, see Figures 1, 7, and 8. More specifically, the horizontal (x) variations of peak altitude $z_* = z_*(x)$ and peak electron density $N_{e*} = N_{e*}(x)$ in Eq. (15) are prescribed by the ad hoc parametrizations

$$z_*(x) \quad = \quad z_{*,\mathrm{min}} + \Delta z_* \cdot f(x)\ , \tag{1}$$

$$N_{e*}(x) \quad = \quad N_{e*,\mathrm{max}} - \Delta N_{e*} \cdot f(x)\ , \tag{2}$$

with

$$f(x) \ = \ \frac{1}{2}\left\{1+\cos\left(\frac{4\pi x}{x_\mathrm{R}-x_\mathrm{L}}\right)\right\} \tag{3}$$

so that $f = f(x)$ varies between zero and one. The parameters x_L and x_R are the horizontal boundaries of the modeling domain, here chosen to be $x_\mathrm{L} = -2000\,\mathrm{km}$ and $x_\mathrm{R} = 2000\,\mathrm{km}$. The values of the electron density peak parameters used in the model runs leading to Figures 1, 7, 8 are as follows: $z_{*,\mathrm{min}} = 110\,\mathrm{km}$, $\Delta z_* = 10\,\mathrm{km}$, $N_{e*,\mathrm{max}} = 1.5\cdot 10^{11}\,\mathrm{m}^{-3}$, $\Delta N_{e*} = 0.5\cdot 10^{11}\,\mathrm{m}^{-3}$.

All LTI model parameters for the simulation runs of the current report, including the horizontal electron density profile parameters, are provided in the configuration file `DIPContBas.py` as part of the supplementary material.

Furthermore, the third introductory paragraph to Section 4 was amended as follows.

Since the physics of energetic particle precipitation is not incorporated in this initial version of the DIPCont package, the horizontal variation of electron density expected for an auroral oval crossing is prescribed through ad hoc choices of horizontal electron density peak parameter~~s~~ profiles, see the option `LTIModelType='NeAuroralZoneCrossing'` in the DIPCont code as part of the supplementary material to this report. The functional forms of horizontal electron density peak parameters are given in Appendix D.

> The authors use a constant magnetic field for all calculations referring to Figure 1 arguing that the gyro frequencies do not change noticeably in the 100 km of altitude under consideration. (This is surprising since it is very easy to accommodate the changing magnetic field in the analysis.) However, it is not clear if they are allowing the magnetic field to vary with latitude over the tens of degrees included in the simulation shown in Figure 1, 7, and 8. Surely the magnetic field would change over these distances corresponding to different latitudes, as this would influence gyro frequencies and the conductivities. Again, the authors should explain the geophysical circumstances in the calculations. This will help the reader understand the model calculations.

Yes, it would indeed be easy to accommodate the variability of the magnetic field, in both the vertical and the horizontal directions. However, as explained before, this initial version of the DIPCont model is meant to introduce and motivate the probabilistic methodology, and the number of model parameters is intentionally kept to a minimum. Since magnetic measurements and models are significantly more accurate than other LTI observables, including a sophisticated magnetic field model at this stage would only increase the LTI model complexity but not contribute to assessing the most important sources of variability. In future work, variations of magnetic field strength are planned to be taken into account. The following text was added to the manuscript in Section 2.7.

[. . .] In the same way as for other LTI model variables, namely, through the dependence of the parameters in the vector $\mathbf{p} = \mathbf{p}(x)$ (see Subsection 2.8 below) on the coordinate x, horizontal variations of magnetic field strength B and thus ion gyrofrequency Ω_i can be modeled~~.~~ , and are planned to be considered in future work.

> Minor Comment:
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> 2. Although the title refers to in situ measurements, the paper discusses only in situ measurements of state parameters, such as neutral and plasma density and neutral and plasma temperature. Other in situ measurements, for example of electric fields, neutral winds, currents, and energetic particles are not included in the study. Perhaps the title might say, *...in situ state parameter measurements...*

The DIPCont approach is sufficiently general to include electric fields and other observables besides state variables. The setup chosen to demonstrate the methodology in this initial DIPCont paper aims at a proof of concept rather than the complete picture, and thus intentionally concentrates on a limited number of observables and parameters to better control model complexity. It would be misleading to mention state variables so prominently, hence the authors prefer to abstain from further changes of the title.

> Suggestion:
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> 3. There are many other low perigee satellite studies in addition to Daedalus over the last 3 decades. It is suggested that the authors consider mentioning these in their Introduction as it would bolster the importance of the analysis and modeling results reported in their paper. These include the NASA TIMED mission which originally included 2 dipper missions, the NASA Geospace Electrodynamics Constellation that included 4 dippers (Grebowsky and Gervin, 2001), and numerous NASA Explorer missions similar to Daedalus, including the ASTRE Mission (Pfaff et al., 2022).

Thanks for the list of relevant mission proposals. In the new version of the manuscript, they have been included as follows.

[. . .] Since the early 20th century, the LTI has been studied extensively using ground-based remote sensing facilities such as ionosondes and radars, but in all aspects requiring in situ observations it remains underexplored territory. Rocket flights (e.g., Sangalli et al., 2009; Pfaff et al., 2022a) can offer only local and temporally confined information. Major technical challenges have so far prevented a satellite mission to the deep, dense part of the LTI, despite scientific interest, community proposals, and feasibility studies by major space agencies (e.g., Grebowsky and Gervin, 2001; Pfaff et al., 2022b). An early conception of the TIMED mission (e.g., Yee et al., 1999) considered dipper options for in situ investigations of the LTI. A recent initiative along this line is the Daedalus mission proposal (Sarris et al., 2020), submitted to ESA in response to the Explorer 10 Call [. . .]

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