

Response to Referees

We thank both reviewers for their detailed evaluations and constructive feedback. Below we provide a revised point-by-point response that accurately reflects the changes made in the manuscript, as confirmed by the submitted PDF with tracked changes. All colored figures were recolored to follow colorblind-friendly palettes and time series plots were adjusted for improved readability.

Reviewer 1

Major Comment 1:

Reviewer: The study relies on only two days of observational data...

Response: We agree with the reviewer that the limited data volume constrains the generalizability of our conclusions. However, our aim was not to provide an exhaustive intercomparison across all geophysical conditions, but rather to highlight the limitations and discrepancies among methods under quiet, controlled conditions. This intent is explicitly discussed in the manuscript.

Changes in Manuscript:

- Lines 435–439 (line numbers always related to pdf with change-tracking) (Section 5): Added text: "While our analysis is based on only two one-day campaigns, the combination of high-cadence DDM and ionogram observations under quiet conditions offers a uniquely controlled tested. This focused setup allows us to isolate method-inherent discrepancies and assess the stability of derived signatures in a consistent observational environment. Such targeted case studies form a necessary first step toward establishing reliable validation strategies for vertical drift estimation methods using more extensive and diverse datasets in the future."

Major Comment 2:

Reviewer: Include DDM error bars in Figures 5 and 6.

Response: We have included vertical error bars representing standard deviation estimates for the DDM-derived vertical drifts. These values were computed from the residuals of the least-squares fitting process.

Changes in Manuscript:

- Figures 5 and 6 updated to include DDM error bars.
- Line 270-282 (Section 4.1): Added: "Each data point is accompanied by a vertical error bar representing the standard deviation of the individual detections within each measurement window. These error bars reflect the internal variability of the detected reflection points at a given time. Notably, in some parts of the day, the uncertainties are significantly larger—especially in the raw (unsmoothed) data—while in other intervals they remain relatively small."

This variability is primarily related to the number of detected echo points during each measurement. A low number of reflections typically leads to large uncertainties due to reduced statistical confidence in the vertical drift estimate. In contrast, when many reflections are detected, the derived drift value is more stable and the standard deviation correspondingly smaller.

It is important to note that during this special measurement campaign, a very short measurements was used for both ionograms and drift measurements, resulting in reduced sounding time and fewer detected points. In contrast, during regular routine operation, each measurement is based on a significantly longer sounding sequence. Therefore, under standard measurement conditions—typically with repetition intervals of 5 to 15 minutes—substantially lower uncertainties can be expected, leading to more precise drift estimates."

Major Comment 3:

Reviewer: Authors avoid strong critical commentary on performance of the tested methods.

Response: We agree and have revised the Discussion section to clearly articulate the practical limitations of each method, particularly under high-resolution settings. Recommendations are added for choosing appropriate methods under different conditions.

Changes in Manuscript:

- Lines 396-415 (Section 6): Rewritten and added: "While DDM provides stable and consistent results across all time scales, indirect methods relying on characteristic ionospheric heights (e.g., hmF2 or h' at fixed frequencies) are susceptible to significant errors at short temporal resolutions due to their sensitivity to signal quality and the proximity of the sounding frequency to foF2, which may result not only in quantitative uncertainties but also in misinterpretation of apparent height variations as true vertical plasma motion.

Our findings indicate that indirect methods, when applied to high-cadence data, often produce inconsistent and physically implausible drift patterns. These inconsistencies are especially evident in the presence of noise-induced artifacts that resemble wave-like structures but lack consistency across different estimation techniques. Such artifacts can lead to misleading scientific interpretations if not carefully examined. Among the tested techniques, the method using h(3.5 MHz) proved particularly unreliable when foF2 approached 3.5 MHz, a situation in which the method consistently failed to provide meaningful results. In this regard, the hmF2-based approach appears to be the most stable among the indirect techniques.

The use of indirect methods becomes practically infeasible at very short time steps. Our findings suggest that a temporal resolution of approximately 15 minutes represents the practical lower limit for obtaining consistent results with indirect methods. In contrast, a 5-minute step—which corresponds to the standard ionogram cadence at some stations—still frequently yields unstable and inconsistent drift estimates. Therefore, in the following discussion we focus on results derived from 15-minute averaged inputs. Even at this time scale, however, notable discrepancies between the individual methods persist in many cases."

Minor Comments:

L. 73–75: Clarify fixed-frequency requirement for Digisonde drift mode.

Response: Corrected.

Changes:

- L. 73-75 (Section 1.3): Added sentence: "Digisonde drift measurements are performed in a dedicated fixed-frequency mode that does not produce ionograms during the measurement intervals and therefore do not provide information about the full ionospheric profile."

L. 104: Acknowledge Wright and Pitteway (1994).

Response: The citation has been added.

Changes:

- Line 104 (Section 2.1): Reference to Wright and Pitteway (1994) included in sentence on development of drift estimation.

L. 217: Clarify that several minutes refers to cadence, not sweep duration.

Response: Sentence revised.

Changes:

- Line 217-223: Changed to: "Historically, standard ionogram soundings were typically performed at 15-minute intervals at most ionospheric stations worldwide. Hourly values of key ionospheric parameters were then usually manually scaled and submitted to central databases. When using a Digisonde in standard operating mode, a single ionogram measurement typically takes about 1–2 minutes, depending on the specific configuration (such as the range of sounding frequencies and the frequency step). In recent years, some stations have adopted denser sounding schedules, with standard cadences of 5 minutes."

Section 4.2 – smoothing clarification:

Response: Clarified that smoothing is applied after the drift calculation.

Changes:

- Line 349-354 (Section 4.2): Added text: "For clarity, we note that the vertical drift values were first computed as differences of height parameters (e.g., Δh_{mF2}) measured at time-separated ionograms, using predefined time intervals Δt (1, 5, 15, 30, or 60 minutes). The resulting time series was then smoothed using a centered moving average. We also tested the reverse procedure—smoothing the height parameters first and then computing drift—and found no significant differences in the final smoothed time series. We therefore retained the direct-differencing approach for its simplicity and better control over temporal structure."

Reviewer 2

Comment 1:

Reviewer: Outline applicability to standard cadence datasets.

Response: We added a statement to Section 5 discussing how our approach could be extended to long-term datasets at 5-minute cadence.

Changes in Manuscript:

- Lines 413–415 (Section 5): Text added: "In contrast, a 5-minute step—which corresponds to the standard ionogram cadence at some stations—still frequently yields unstable and inconsistent drift estimates. Therefore, in the following discussion we focus on results derived from 15-minute averaged inputs. Even at this time scale, however, notable discrepancies between the individual methods persist in many cases."

Comment 2:

Reviewer: Discuss and interpret DDM standard deviations.

Response: Addressed. A new paragraph in Section 5 explains the variation in DDM uncertainty and its practical implications.

Changes in Manuscript:

- Line 270-282 (Section 4.1): Added: "Each data point is accompanied by a vertical error bar representing the standard deviation of the individual detections within each measurement window. These error bars reflect the internal variability of the detected reflection points at a given time. Notably, in some parts of the day, the uncertainties are significantly larger—especially in the raw (unsmoothed) data—while in other intervals they remain relatively small."

This variability is primarily related to the number of detected echo points during each measurement. A low number of reflections typically leads to large uncertainties due to reduced statistical confidence in the vertical drift estimate. In contrast, when many reflections are detected, the derived drift value is more stable and the standard deviation correspondingly smaller.

It is important to note that during this special measurement campaign, a very short measurements was used for both ionograms and drift measurements, resulting in reduced sounding time and fewer detected points. In contrast, during regular routine operation, each measurement is based on a significantly longer sounding sequence. Therefore, under standard measurement conditions—typically with repetition intervals of 5 to 15 minutes—substantially lower uncertainties can be expected, leading to more precise drift estimates."

Additional Revisions:

- All colored plots revised using colorblind-friendly palettes (Color Universal Design).

- Time series figures redesigned for clarity (thinner lines, consistent colors, improved legends).

We hope these changes meet the expectations of the reviewers and editor, and we thank you again for the opportunity to improve our manuscript.

The tracked-changes manuscript is included.