Reply on RC1

Question: This paper describes the world's first attempt to evaluate image navigation validation (INV) in the longwave (LW) bands of the FY-4A GIIRS using the ground-based laser positioning system (GLPS). It contains engineering innovations that deserve high recognition in the field of remote sensing. The verification concept utilizing multiple stations over long baselines and the introduction of multiple subpixel evaluation methods are of high practical value. However, the current manuscript reads like an unpolished preprint. Errors in the basic physical understanding of the observation geometry, inconsistencies in coordinate systems and parameter settings between the text and figures/tables, and redundant descriptions are found throughout. There are also many unexplained abbreviations, making some portions difficult to understand. Furthermore, there is a critical self-contradiction within the paper. To ensure the reliability and reproducibility of the paper as an academic publication, it is necessary to fundamentally restructure the entire manuscript in accordance with the following comments.

Our reply: We sincerely thank the reviewer for the thorough evaluation of our manuscript and for recognizing the engineering innovations and practical significance of this study, particularly the use of geographically separated ground-based laser stations and multiple subpixel navigation validation methods. We greatly appreciate this positive assessment of the novelty and potential contribution of our work.

We have taken all the reviewer's comments very seriously and have made comprehensive and substantial revisions to the manuscript. In particular, we have clarified the observation geometry and underlying physical principles, improved the consistency of coordinate systems, figures, tables, and parameter definitions, eliminated redundant descriptions, standardized terminology and abbreviations, and thoroughly polished the English throughout the manuscript. We have also reorganized the relevant sections and clarified the relationship between visible- and infrared-channel navigation to address the apparent inconsistency identified by the reviewer. **All specific and technical comments have been carefully addressed, and the corresponding revisions have been incorporated into the manuscript.**

We believe these extensive revisions have significantly improved the scientific rigor, logical coherence, reproducibility, and overall quality of the manuscript. We sincerely hope that these improvements will address the reviewer's concerns and allow the scientific contribution and practical value of this work to be reassessed favorably.

We sincerely appreciate the reviewer's valuable comments and the time devoted to helping us improve the manuscript.

Specific comments

Question1: *The Introduction contains too many details regarding the methods and results (starting with the sentence "For each detector..." at L76) and repeats the same explanations found in Section 4, such as the "weighted gray center method," "Kriging method," and number of images, resulting in redundancy. The text in the Introduction should be kept concise, and the duplication with Section 4 should be eliminated.*

Our reply: Thank you for this valuable suggestion. We have revised and streamlined the Introduction to reduce unnecessary methodological details and eliminate redundancy with Section 4. The detailed descriptions of the laser signal detection and navigation deviation estimation methods are now presented in Section 4, while the Introduction focuses on the research background, motivation, objectives, and main contributions. Only a brief overview of the proposed methods has been retained to highlight the novelty of this study. These revisions have improved the logical organization and readability of the manuscript. The following is the revised content of the introduction:

"The Geostationary Interferometric Infrared Sounder (GIIRS) onboard the Fengyun-4A (FY-4A) satellite is the world's first hyperspectral infrared sounder operating from a geostationary platform. It provides atmospheric observations with high temporal resolution and vertical profiling capabilities, supporting nowcasting and numerical weather prediction (Yang et al., 2017; Di et al., 2025). Accurate assessment of image navigation and registration performance is essential for evaluating the geolocation accuracy of satellite observations and monitoring navigation performance throughout the instrument's operational lifetime (Grycewicz et al., 2016; De Luccia et al., 2016).

Image navigation accuracy can be evaluated using landmark registration and star observations. Landmark-based methods estimate navigation deviations by matching ground control points identified in satellite images with their corresponding geographical references (Emery et al., 2003; Yang et al., 2011; Wang et al., 2017; Hou et al., 2020). However, cloud contamination and insufficient identifiable features may reduce matching accuracy or lead to matching failures. Star observations provide an alternative reference that is unaffected by terrestrial cloud cover and can be used to monitor instrument pointing variations (Jiang et al., 2021; Li et al., 2019; Tan et al., 2018). For FY-4A instruments, star-based observations have been used to support geometric calibration and compensate for pointing variations associated with thermal deformation (Shang et al., 2017, 2019). Nevertheless, conventional methods remain challenging for instruments or channels that cannot directly observe stars or identify sufficient landmarks, such as the infrared channels of GIIRS and the FY-4A Lightning Mapping Imager (LMI; Wang et al., 2021).

GIIRS is equipped with a visible focal plane with a spatial resolution of 2 km and two infrared channels, namely the medium-wave (MW) and longwave (LW) channels, with a spatial resolution of 16 km. The infrared image navigation relies on corrections derived from visible-channel star observations and pre-

calibrated inter-channel registration parameters. However, because the visible and infrared channels follow separate optical paths, uncertainties in inter-channel registration may introduce additional navigation errors. Consequently, visible-channel navigation accuracy cannot directly represent the actual navigation accuracy of the infrared channels. Furthermore, the relatively low spatial resolution and staggered detector arrangement of the infrared channels make direct landmark-based validation challenging, while direct star-based validation is unavailable. Therefore, an independent approach is required to assess the actual navigation accuracy of the infrared channels.

Ground-based laser measurements provide an alternative validation approach by using precisely geolocated laser stations as reference points. Buechler et al. (2018) investigated the use of ground-based laser beacons to validate the geolocation accuracy of the Geostationary Lightning Mapper (GLM) onboard GOES-16. The Chinese ground-based laser positioning system (GLPS) program for FY-4A GIIRS was initiated in January 2016, approximately coinciding with the development of ground-based laser beacons for GOES-16 GLM. The first GLPS station for FY-4A was completed in December 2017, including infrastructure construction, laboratory renovation, and laser system commissioning. Both approaches share the fundamental principle of using laser signals transmitted from precisely geolocated ground stations as reference points for on-orbit geolocation validation. However, unlike the GLM, GIIRS is a hyperspectral infrared sounder with distinct spectral response characteristics and a staggered detector array. To accommodate these characteristics, the GLPS was specifically designed to transmit laser signals at approximately 10.591 μm, within the spectral response range of the GIIRS LW channel. Key system parameters, including laser wavelength, transmitting power, power stability, and the expected signal-to-noise ratio of the LW detectors, were carefully evaluated to ensure reliable laser signal detection. Furthermore, two dedicated observation modes, namely dwell observation and step scanning, are designed to accommodate the staggered detector arrangement and scanning characteristics of GIIRS. Corresponding algorithms are developed for laser signal detection and navigation deviation estimation. These instrument-specific developments extend the applicability of ground-based laser validation techniques from lightning imagers to hyperspectral infrared sounders.

In this study, a satellite–ground integrated method is developed to independently validate the image navigation accuracy of the FY-4A GIIRS LW channel using the GLPS. The proposed method combines dedicated satellite observation strategies with laser signal detection and navigation deviation estimation methods. Its effectiveness is evaluated using actual on-orbit observations, and the resulting navigation deviations are compared with those obtained from visible-channel observations. The main contributions of this study are summarized as follows:

(1) A GLPS is developed to independently validate the image navigation accuracy of the FY-4A GIIRS LW channel. Key system parameters, including laser wavelength, transmitting power, beam characteristics, and expected signal-to-noise ratio, are carefully selected and evaluated to ensure reliable detection by the LW detectors.

(2) Two dedicated observation modes, dwell observation and step scanning, are designed to accommodate the staggered arrangement of the GIIRS detector array. These modes provide complementary observations for estimating navigation deviations at the pixel and subpixel levels.

(3) Dedicated algorithms are developed for laser signal detection and navigation deviation estimation. A laser index algorithm is introduced to identify laser signals in the LW observations, while a weighted gray-level centroid method and Kriging interpolation are applied to dwell and step-scanning observations, respectively, to estimate navigation deviations in the east–west and north–south directions."

Question2 : *Table 1: The definitions of wavenumbers are listed in reverse order, such as LW (1650-2250) and MW (700-1130). Please align them with the correct description in L104.*

Our reply: Thank you for identifying this error. We have corrected the spectral ranges of the LW and MW channels in Table 1. The LW channel is now correctly specified as 700–1130 cm^{-1}, while the MW channel is specified as 1650–2250 cm^{-1}. These values are consistent with the corresponding description in Section 2.

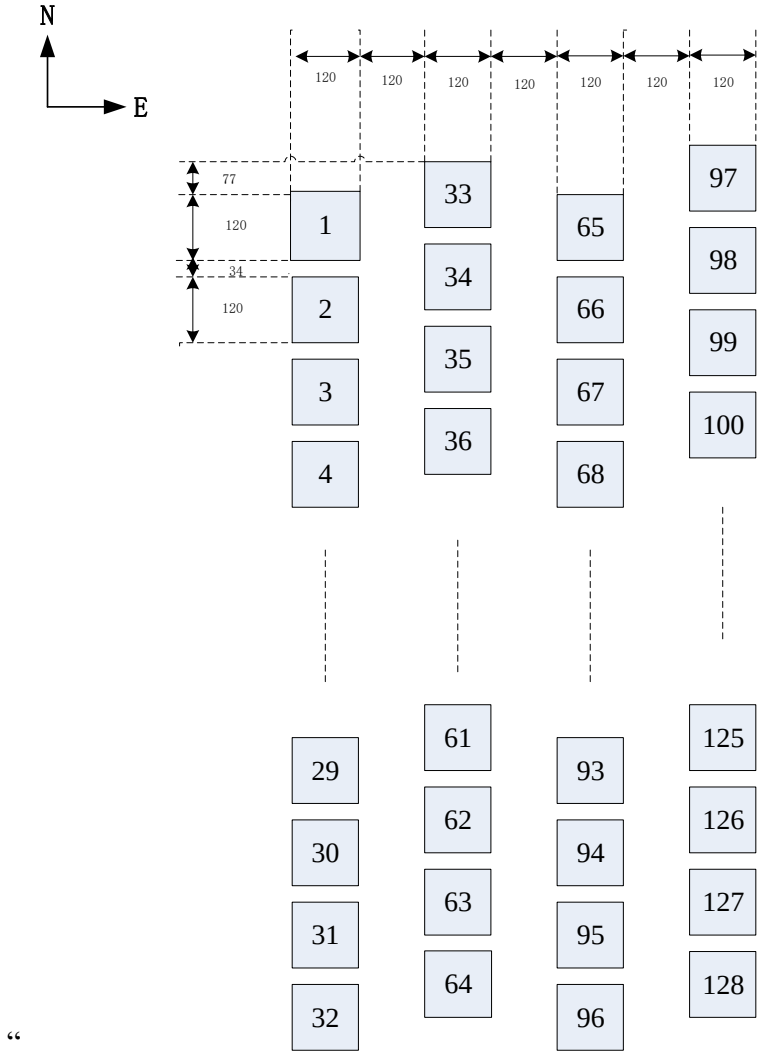
"Table 1. Main instrument characteristics of FY-4A GIIRS.

Parameter	Specification
Spectral coverage	Visible: 0.55–0.75 μm LW: 700–1130 cm^{-1} MW: 1650–2250 cm^{-1}
Temporal resolution	35 min (1000 km × 1000 km) 67 min (5000 km × 5000 km)
Limiting star magnitude	6.5 Mag (visual channel)
Radiometric calibration accuracy	1.5 K
Spectral calibration accuracy	10 ppm

"

Question3: *Fig. 1: The caption states, "The units of the numbers in the figure are μm," but the numbers inside the boxes (15, 47, 48, etc.) are detector index numbers, so this description is inappropriate. Additionally, clearly indicate in the figure the dimensions mentioned in the text: "The first and second columns have a misalignment of 77 μm." Also, clearly state in the caption that the figure is an enlarged view of the central portion of the 32×4 array.*

Our reply: Thank you for pointing out the ambiguity in Figure 1. We have revised the figure and its caption to distinguish detector index numbers from physical dimensions. The 77 μm offset between adjacent detector columns is now explicitly indicated in the figure. We have also clarified that the illustration is a schematic representation of the staggered 32 × 4 detector array, with portions omitted for clarity. These modifications make the detector arrangement and its geometrical characteristics easier to understand. The following presents the corresponding revisions in the manuscript.



“

Figure 1: Figure 1. Schematic illustration of the staggered 32 × 4 detector array in the GIIRS infrared focal plane. Numbers inside the detector boxes indicate detector indices, whereas numerical annotations associated with dimension lines represent physical distances in micrometers (μm). The relative offset of 77 μm between adjacent detector columns is indicated. The arrows denote the north (N) and east (E) directions. Portions of the array are omitted for clarity.”

Question4: *L118-121: The paragraphs on calibration tasks using blackbodies and the Moon are unrelated to this study (laser-based position verification) and should therefore be deleted.*

Our reply: Thank you for this suggestion. We agree that the detailed discussion of blackbody, cold-space, and lunar calibration activities is not directly relevant to the laser-based image navigation validation investigated in this study. We have therefore removed the unrelated descriptions and retained only the information necessary to explain the observation modes and navigation validation framework of GIIRS. This revision improves the focus and conciseness of Section 2.

Question5: *Fig. 2: Specify the latitudes and longitudes of the Jiamusi station and the Xinjiang station. The description "similar latitudes" (L134) alone is ambiguous.*

Our reply: Thank you for this valuable suggestion. We agree that providing the precise geographical coordinates of the two GLPS stations is important for clearly describing the experimental configuration. Accordingly, we have added the latitude and longitude of both stations in Section 3.2 and revised the caption of Figure 2. Specifically, the Jiamusi station is located at 133.4°E, 46.8°N, while the Xinjiang station is located at 87.6°E, 43.9°N.

"*Two GLPS stations were established at geographically separated locations within the GIIRS field of view: one in Jiamusi, Heilongjiang Province (133.4°E, 46.8°N), and the other in Xinjiang (87.6°E, 43.9°N), China (Fig. 2). The two GLPS stations are observed at scheduled times according to their respective observation tasks. During each observation, the GIIRS two-dimensional scanning mirrors adjust the pointing direction toward the target station based on its geographical coordinates and the satellite position, so that the laser signal is ideally imaged onto the central reference detector (No. 48). Thus, both stations are observed under approximately on-axis imaging conditions, and their different viewing geometries are accounted for through independent pointing adjustments.*

Figure 2: Geographical locations of the GLPS stations in Jiamusi, Heilongjiang Province (133.4°E, 46.8°N), and Xinjiang (87.6°E, 43.9°N), China. The station locations are indicated by red circles. Base map © Baidu Maps."

Question6: *L134-135: The text argues that the effect of parallax can be ignored because "the latitudes of the Jiamusi and Xinjiang stations are nearly the same," but the two stations are significantly distant from each other in the longitude direction, and considering the curvature of the Earth, their line-of-sight angles are entirely different. In other words, this statement does not constitute a geometrically valid justification.*

Our reply: Thank you for this insightful comment. We agree that the similarity in latitude between the Jiamusi and Xinjiang stations alone is insufficient to justify neglecting parallax effects, particularly given their substantial longitudinal separation and the resulting differences in satellite viewing geometry.

We would like to clarify that the two GLPS stations are observed at different times rather than simultaneously. During each observation, the two-dimensional scanning mirror system of GIIRS independently adjusts the instrument's pointing direction toward the corresponding ground station based on its known geographical coordinates and the satellite position. The scanning mirrors are commanded to align the instrument's optical axis with the target station, so that the laser signal is ideally imaged onto the designated central reference detector (No. 48). Therefore, observations of both stations are conducted under approximately on-axis imaging conditions, despite their different geographical locations and line-of-sight directions.

Since the two stations are observed separately, the viewing geometry is

independently determined and the scanning mirror orientation is adjusted for each observation. Consequently, the longitudinal separation between the stations does not directly introduce a relative displacement of the laser image from the reference detector under ideal pointing conditions. The proposed validation method does not rely on the assumption that the two stations have identical viewing geometries.

We have revised Section 3.2 to clarify the time-separated observation strategy, the independent adjustment of the scanning mirrors, and the approximately on-axis imaging configuration. We have also removed the original justification based solely on the similarity of the station latitudes.

"The two GLPS stations are observed at scheduled times according to their respective observation tasks. During each observation, the GIIRS two-dimensional scanning mirrors adjust the pointing direction toward the target station based on its geographical coordinates and the satellite position, so that the laser signal is ideally imaged onto the central reference detector (No. 48). Thus, both stations are observed under approximately on-axis imaging conditions, and their different viewing geometries are accounted for through independent pointing adjustments."

We sincerely appreciate the reviewer's comment, which has helped us clarify the observation geometry and the underlying principles of the proposed validation method.

Question7: *L224: Provide a clear definition of the thresholds for the "weak/strong laser" intensity classifications.*

Our reply: Thank you for this valuable comment. We agree that clearly defining the thresholds for laser signal intensity classification is important for ensuring the clarity and reproducibility of the proposed method. Based on the intensity characteristics of laser signals obtained from a large number of actual observations, we have determined the classification thresholds. Specifically, a laser signal is classified as weak when its laser index is greater than 10 and less than 20 radiation value units, and as strong when its laser index exceeds 20 radiation value units. These classification criteria have been explicitly added to Section 4.2.1 of the revised manuscript to provide a clearer and more reproducible description of the laser signal detection procedure.

"*Based on the intensity characteristics of laser signals obtained from a large number of observations, the classification thresholds are determined. Specifically, a laser signal is classified as weak when its laser index is greater than 10 and less than 20 radiation value units, and as strong when its laser index exceeds 20 radiation value units.*"

Question8: *Fig. 7: The legend includes "band 389" and "band 392," which are not mentioned in the text. Please provide a quantitative explanation in the text regarding their relationship to the laser center wavelength.*

Our reply: Thank you for this valuable comment. We have clarified the relationship between the spectral channels shown in Figure 7 and the laser center wavelength in Section 5.2. The measured center wavelength of the ground-based laser is 10.591 μm, corresponding to a wavenumber of 944.198 cm^{-1}. Given the spectral range of 700–1130 cm^{-1} and spectral resolution of 0.625 cm^{-1} for the GIIRS LW channel, the corresponding spectral channel index is calculated as (944.198 − 700)/0.625 + 1 = 391.7168, which is approximately band 392. Band 389 is selected as a representative neighboring channel within the 10-channel spectral window around band 392 to illustrate the background spectral response.

Figure 7 presents four representative cases from actual laser observations. In Figure 7a, no noticeable response changes are observed in band 392 or its neighboring channels when no laser signal is present. In Figure 7b, under weak laser signal conditions, the maximum radiance response does not necessarily indicate a valid laser signal. In Figures 7c and 7d, strong laser signals produce a pronounced response peak at band 392, with an enhanced response also observed in the adjacent band 393 (maxband + 1). These explanations have been added to Section 5.2 to improve the clarity of Figure 7.

"*The measured center wavelength of the ground-based laser is 10.591 μm, corresponding to a wavenumber of 944.198 cm^{-1}. Based on the GIIRS LW spectral range (700–1130 cm^{-1}) and spectral resolution (0.625 cm^{-1}), the corresponding channel index is calculated as (944.198 − 700)/0.625 + 1 = 391.7168, approximately corresponding to band 392. Band 389 is selected as a representative neighboring channel within the 10-channel spectral window to illustrate the background spectral response.*"

Question9: *Fig. 8: Although lines 240-241 define the "x-axis as the EW direction and the y-axis as the NS direction," the scatter plot in Figure 8 has the x-axis set to the NS direction and the y-axis to the EW direction, making it difficult to interpret. It is recommended that the axes be corrected to match the definition. Additionally, adjusting the aspect ratio of the figure to 1:1 would likely make it easier to interpret.*

Our reply: Thank you for identifying the inconsistency in the coordinate definitions. We have revised Figure 8 so that the x-axis represents the east–west (EW) direction and the y-axis represents the north–south (NS) direction, consistent with the definitions in Section 4.2. We have also reviewed the axis ranges and figure layout to improve the clarity and comparability of the navigation deviations in the two directions. These revisions ensure consistency between the figure and the corresponding methodological descriptions.

Question10: *Fig. 9: Although the differences in interpolation conditions, such as "grid is 4" and "grid is 100", are shown, the main text lacks an explanation of the*

intent behind these settings or a discussion of the comparison results. Please state in the main text the reasons and intent for changing the interpolation conditions. Also, clearly specify in the captions which figure represents "Powerful intensity" and which represents "Medium intensity.".

Our reply: Thank you for this valuable comment. We have clarified the purpose of using different grid settings in the Kriging interpolation and revised the caption of Figure 9 accordingly.

Specifically, the grid parameter determines the spatial resolution of the interpolated results and, consequently, the minimum increment used to estimate navigation deviations. When the grid parameter is set to 4, the navigation deviation can be estimated in increments of 0.25 pixels, whereas a grid parameter of 100 allows a finer increment of 0.01 pixels. These two settings were used to illustrate the influence of interpolation grid density on the granularity of navigation deviation estimation. A denser interpolation grid enables more precise localization of the interpolated laser response peak, although it does not necessarily improve the actual navigation accuracy.

Furthermore, we have clarified that Figures 9a and 9b correspond to strong laser signals, while Figures 9c and 9d correspond to moderate-intensity laser signals. The corresponding explanations have been added to Section 5.4 and the caption of Figure 9.

"*A grid parameter of 4 corresponds to a spatial increment of 0.25 pixels, whereas a grid parameter of 100 provides a finer increment of 0.01 pixels, enabling finer localization of the interpolated laser response peak. Figures 9a and 9b show the results obtained under strong laser signal conditions, where the interpolated response distributions exhibit a pronounced peak. In contrast, Figures 9c and 9d correspond to weak laser signals, for which multiple local peaks may occur, although a dominant peak can still be identified.*

Figure 9. Laser response distributions obtained from GIIRS LW step-scanning observations using Kriging interpolation. (a, b) Strong laser signals observed at 15:00 UTC on 26 April 2019. (c, d) Weak laser signals observed at 13:00 UTC on 25 April 2019. Panels (a) and (c) use a grid parameter of 4, corresponding to a spatial increment of 0.25 pixels, while panels (b) and (d) use a grid parameter of 100, corresponding to a finer increment of 0.01 pixels."

Question11: *L292: How do "powerful/medium" correspond to "weak/strong" in L224?*

Our reply: Thank you for pointing out the inconsistency in the terminology used to describe laser signal intensity. We have reviewed and standardized the intensity classifications throughout the manuscript to avoid ambiguity. The terminology in the methodological descriptions, results analysis, and figure captions has been made consistent with the classification criteria defined in Section 4.2.1. This revision ensures that the laser intensity categories are used consistently throughout the study.

"*Figures 9a and 9b show the results obtained under strong laser signal conditions, where the*

interpolated response distributions exhibit a pronounced peak. In contrast, Figures 9c and 9d correspond to weak laser signals, for which multiple local peaks may occur, although a dominant peak can still be identified.

Figure 9: Laser response distributions obtained from GIIRS LW step-scanning observations using Kriging interpolation. (a, b) Strong laser signals observed at 15:00 UTC on 26 April 2019. (c, d) Weak laser signals observed at 13:00 UTC on 25 April 2019. Panels (a) and (c) use a grid parameter of 4, corresponding to a spatial increment of 0.25 pixels, while panels (b) and (d) use a grid parameter of 100, corresponding to a finer increment of 0.01 pixels."

Question12: *L297-302: The comparison with the visible band in Section 5.5 fundamentally contradicts the core motivation for this study as stated by the authors in the Introduction. In L56-61, the authors explicitly state, "It is not appropriate to use the visible band to directly verify the INR of infrared bands." The very fact that the optical paths are independent should have been the legitimate justification for developing the new GLPS technology in this paper. Nevertheless, at L298, the authors fall into a self-contradiction by using landmark verification results from the visible band, which the authors themselves declared inappropriate, to prove the reliability of GLPS. The authors' attempt to prove the validity of the proposed method using a method they themselves described as inappropriate as a verification tool undermines the scientific credibility of the paper, and verification using an alternative method is necessary.*

Our reply: Thank you for this insightful comment. We apologize for the insufficient clarification in the original manuscript. To address this concern, we have expanded the description of the GIIRS image navigation principles in the Introduction and Section 2 to clarify the relationship between the visible and infrared channels and explain the rationale for comparing their navigation results.

Although the visible and infrared channels of GIIRS follow separate optical paths, the visible channel supports image navigation through star-based geometric calibration throughout the diurnal cycle and has a much higher spatial resolution. The resulting navigation corrections are transferred to the infrared channels through pre-calibrated channel-channel registration parameters. Despite potential channel -channel registration errors, visible-channel landmark validation provides a relatively reliable reference compared with direct landmark-based validation of the coarse-resolution infrared channels. However, visible-channel navigation accuracy cannot directly represent the actual navigation accuracy of the infrared channels, which motivates the development of the GLPS-based independent validation method.

Therefore, the visible-channel navigation results are included in Section 5.5 only as a reference for assessing the consistency of the two approaches, rather than as direct verification of infrared navigation accuracy or proof of the GLPS method's reliability.

The comparable navigation deviations provide additional support for the plausibility of the GLPS-based results. Thus, the comparison is consistent with, rather than contradictory to, the motivation for independent infrared navigation validation.

We have clarified these points in the Introduction, Section 2, and Section 5.5. Furthermore, future work will explore geometric co-registration between the GIIRS interferometer and satellite imagers as an additional approach for validating the navigation accuracy of both the MW and LW channels. We sincerely appreciate the reviewer's constructive suggestion.

"Introduction:

GIIRS is equipped with a visible focal plane with a spatial resolution of 2 km and two infrared channels, namely the medium-wave infrared (MW) and longwave infrared (LW) channels, with a spatial resolution of 16 km. The infrared image navigation relies on corrections derived from visible-channel star observations and pre-calibrated inter-channel registration parameters. However, because the visible and infrared channels follow separate optical paths, uncertainties in inter-channel registration may introduce additional navigation errors. Consequently, visible-channel navigation accuracy cannot directly represent the actual navigation accuracy of the infrared channels. Furthermore, the relatively low spatial resolution and staggered detector arrangement of the infrared channels make direct landmark-based validation challenging, while direct star-based validation is unavailable. Therefore, an independent approach is required to assess the actual navigation accuracy of the infrared channels.

Section 2:

The image navigation of FY-4A GIIRS is achieved through coordinated satellite–ground operations, involving attitude motion compensation (AMC), orbit motion compensation (OMC), and thermal deformation compensation (TMC; Xu et al., 2024). The ground system predicts observable stars and generates observation schedules and commands based on satellite orbit information and instrument operating conditions. GIIRS then performs scheduled star observations using its visible channel, and the acquired data are transmitted to the ground system for processing. The observed star centroids are extracted and compared with their predicted positions to determine pointing deviations. Based on these deviations, thermal deformation correction parameters are derived and uploaded to the satellite. Together with attitude and orbit motion compensation, these parameters are applied to correct the scanning mirror pointing angles and maintain the accuracy of the instrument's line of sight. For the LW and MW channels, the navigation corrections derived from visible-channel observations are transferred through pre-calibrated inter-channel registration parameters to determine the geographical locations of infrared observations. However, because the visible and infrared channels follow separate optical paths, uncertainties in inter-channel registration may introduce additional navigation errors. Therefore, independent validation is necessary to assess the actual navigation accuracy of the infrared channels.

Section 5.5:

To assess the consistency of the GLPS-based validation results, the LW navigation deviations are compared with those obtained from visible-channel landmark observations. As described in Section 2, the visible channel supports GIIRS image navigation through star-based geometric calibration

throughout the diurnal cycle and has a higher spatial resolution. Although potential inter-channel registration errors prevent visible-channel navigation accuracy from directly representing infrared navigation accuracy, the visible-channel results provide a useful reference for comparison.

Because the two channels have different spatial resolutions, the navigation deviations are converted into kilometers for comparison. As shown in Table 3, the two approaches yield navigation deviations of comparable magnitude, although some differences remain, particularly in the EW direction. This agreement provides a consistency check that supports the plausibility of the GLPS-based results, rather than serving as direct verification of infrared navigation accuracy. The GLPS therefore remains an independent method for validating the navigation performance of the GIIRS LW channel."

Question13: *L305-313: In the "Conclusion", a summary and comparison regarding "Dwell observations and Step scanning observations (L90-91)"—which were cited as a contribution of this study—are completely missing. The numerical values presented in the conclusion (EW 0.35 pixels, NS 0.45 pixels) are based solely on the Step scanning results, while the results of the Dwell observations are ignored. The main text must be rewritten to properly conclude the paper's narrative by including a scientific discussion of the accuracy comparison between the two modes (though there is some mention of this in L287-290) and an explanation of why it was necessary to use both modes in conjunction (even if this was due to observational operational constraints).*

Our reply: Thank you for this valuable comment. We agree that the Conclusion should summarize the results obtained from both observation modes and explain their complementary roles in image navigation validation.

We have revised the Conclusion to include the results from both dwell observation and step scanning. The dwell observation results showed navigation deviations within 0.2 pixels in the EW direction and 0.4 pixels in the NS direction, while the step-scanning results showed deviations within 0.35 and 0.45 pixels, respectively. Although the two modes employ different spatial sampling strategies and estimation methods, their results are generally consistent in magnitude.

We have also clarified that dwell observation provides navigation deviation estimates from a fixed detector configuration, while step scanning enables finer spatial sampling to mitigate the influence of the staggered detector arrangement. Their complementary use provides a more comprehensive assessment of the GIIRS LW navigation performance.

We sincerely appreciate the reviewer's suggestion, which has helped improve the completeness and scientific clarity of the Conclusion.

"*Dwell observations showed navigation deviations within 0.2 pixels in the east–west (EW) direction and 0.4 pixels in the north–south (NS) direction, while step-scanning observations yielded deviations within 0.35 and 0.45 pixels, respectively. The results were generally comparable in magnitude. Dwell observation provides navigation deviation estimates using a fixed detector configuration, whereas step*

scanning enables finer spatial sampling to mitigate the effects of the staggered detector arrangement. Together, these complementary modes demonstrate the feasibility of GLPS-based independent validation of GIIRS LW image navigation."

Question14: *L305-313: In the "Conclusion," there is no discussion of the three methods (laser index, gray centroid method, and Kriging method) presented as the contributions of this study, making the narrative of the paper incomplete.*

Our reply: Thank you for this constructive suggestion. We agree that the methodological contributions should be explicitly summarized in the Conclusion.

Accordingly, we have revised the Conclusion to clarify the respective roles of the three methods. The laser index algorithm is used to identify laser signals from the LW spectral observations. The weighted gray-level centroid method is applied to dwell observations to estimate navigation deviations, while Kriging interpolation is employed in step-scanning observations to reconstruct the spatial distribution of laser responses and estimate navigation deviations at the subpixel level.

These additions provide a more complete summary of the proposed validation framework and strengthen the logical connection between the methodology, experimental results, and conclusions. We sincerely appreciate the reviewer's helpful comment.

"*This study developed a ground-based laser positioning system (GLPS) for independent validation of the FY-4A GIIRS longwave infrared (LW) image navigation accuracy. A laser index algorithm was used to detect laser signals, while the weighted gray-level centroid method and Kriging interpolation were applied to dwell and step-scanning observations, respectively, to estimate navigation deviations.*"

Technical corrections

Question1: *It is recommended that the full names of the abbreviations used in the abstract be provided the first time they appear in the main text following the introduction. These include INV, LW, GIIRS, FY-4A, and GLPS.*

Our reply: Thank you for this suggestion. We have carefully reviewed the abbreviations used throughout the manuscript and provided their full names at their first occurrence in the main text. In particular, the definitions of image navigation validation (INV), longwave infrared (LW), Geostationary Interferometric Infrared Sounder (GIIRS), Fengyun-4A (FY-4A), and ground-based laser positioning system (GLPS) have been checked and clarified. These revisions improve the readability of the manuscript and make the terminology more accessible to readers.

Question2: *L35-36 and L98-99: The phrase "the world's first hyperspectral infrared sounder on a geostationary platform" is repeated, which is redundant. Please*

rephrase or delete it.

Our reply: Thank you for pointing out this redundancy. We have removed the repeated description of GIIRS as the world's first hyperspectral infrared sounder on a geostationary platform from Section 2. The revised text now focuses on the instrument characteristics without repeating information already presented.

Question2: *L35-36 and L98-99: The phrase "the world's first hyperspectral infrared sounder on a geostationary platform" is repeated, which is redundant. Please rephrase or delete it.*

Our reply: Thank you for pointing out this redundancy. We have removed the repeated description of GIIRS as the world's first hyperspectral infrared sounder on a geostationary platform from Section 2. The revised text now focuses on the instrument characteristics without repeating information already presented.

Question3: *L38: What is the NWP?*

Our reply: Thank you for pointing this out. We have revised the corresponding sentence to use the full term "numerical weather prediction" instead of the unexplained abbreviation "NWP", thereby improving clarity for readers.

Question4: *L38: image navigation and registration performance (INR)?*

Our reply: Thank you for this comment. To avoid unnecessary abbreviations and improve the readability of the manuscript, we have removed the abbreviation "INR".

Question5: *L42: What is the GCP?*

Our reply: Thank you for this comment. To avoid unnecessary abbreviations and improve the clarity and readability of the manuscript, we have removed the abbreviation "GCP" and consistently used the full term "ground control points" throughout the revised manuscript.

Question6: *6. L56 and L104: "beamsare" → "beams are"?*

Our reply: Thank you for identifying this typographical and grammatical error. We have rewritten the original sentence to improve both its grammatical accuracy and technical clarity. The revised sentence reads:

"*The incoming radiation is split into two optical paths: one directed toward the Michelson interferometer for infrared interferogram measurements and the other focused onto the visible focal plane.*"

This revision also provides a clearer explanation of the optical configuration of GIIRS.

Question7: *L73: "um" → "μm"?*

Our reply: Thank you for identifying this formatting error. We have corrected "um" to the standard unit symbol "μm" in the relevant descriptions of the detector dimensions and spatial offsets. We have also reviewed the corresponding unit notation in the text and figures for consistency.

Question8: *L104: "spilt" → "split"?*

Our reply: Thank you for pointing out this typographical error. We have corrected "spilt" to "split" and rewritten the corresponding sentence to improve clarity and grammatical accuracy. The revised description now clearly explains how the incoming radiation is divided into the infrared and visible optical paths.

Question9: *L172-173 and L175-L176: The phrase "the relative position ..." appears twice; please rephrase or delete it*

Our reply: Thank you for identifying the repeated description. We have revised Section 3.4 to eliminate the redundant explanation of the relative position vector between the satellite and the laser station. The revised text retains the necessary coordinate definitions while providing a more concise transition from the ECEF coordinate system to the local Cartesian coordinate system. This revision improves the clarity and readability of the mathematical description.

"*The relative position vector of the satellite and laser station in ECEF is calculated:*

$$\Delta(\Delta x, \Delta y, \Delta z) = R(X, Y, Z) - R_A(X_A, Y_A, Z_A)$$

where $R_A(X_A, Y_A, Z_A)$ *is the laser station position in ECEF coordinate system. The resulting relative position vector is subsequently transformed into the local Cartesian coordinate system using two rotation matrices.*"

Question10: *L285: In the title of Section 5.4, the text reads "Dwell Observation Data," but since the content refers to step scanning, please correct it to "Step Scanning Data."*

Our reply: Thank you for identifying this inconsistency. We have corrected the title of Section 5.4 from "Dwell Observation Data" to "Step Scanning Data" to accurately reflect the content of this section. The revised heading is now "Analysis of Image Navigation Results Using Step Scanning Data".