Reply on RC3

Question: *In the Introduction, the authors should clearly clarify the similarities and differences between this work and the GOES satellite technique.*

Our Reply: Thank you for this valuable suggestion. We agree that the similarities and differences between the proposed technique and the ground-based laser validation approach previously demonstrated for the GOES satellite should be more clearly explained.

Both approaches share the same fundamental principle of using ground-based laser signals from precisely geolocated stations as reference points for validating the geolocation accuracy of satellite instruments.

However, the two approaches differ in their target instruments, observation characteristics, and validation methodologies. The previous GOES study focused on the Geostationary Lightning Mapper (GLM), whereas our study investigates the longwave infrared (LW) channel of the FY-4A Geostationary Interferometric Infrared Sounder (GIIRS), a hyperspectral infrared instrument. To accommodate the spectral response characteristics of GIIRS, the GLPS employs a laser with a center wavelength of approximately 10.6 μm, enabling direct detection by the LW detectors. Furthermore, considering the staggered arrangement of the GIIRS detector array, two dedicated observation modes, namely dwell observation and step scanning, are designed. Corresponding data processing algorithms are also developed to detect the laser signals and quantify navigation deviations at the pixel and subpixel levels.

Therefore, although both studies employ ground-based laser signals for geolocation validation, the present work extends this approach to a hyperspectral infrared sounder and develops instrument-specific observation strategies and data processing methods to address the particular challenges of GIIRS image navigation validation.

We have revised the Introduction to explicitly clarify these similarities and differences and to better highlight the specific contributions of this study:

"*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."

Question: *It would be better to explain the GIIRS image navigation method.*

Our Reply: Thank you for this valuable suggestion. We agree that a clearer description of the GIIRS image navigation method would help readers better understand the motivation for the proposed image navigation validation approach.

The image navigation of FY-4A GIIRS is achieved through the combined application of attitude motion compensation, orbit motion compensation, and thermal deformation compensation. In particular, star observations are scheduled throughout the diurnal cycle using the visible channel of GIIRS. The observed star centroids are extracted and compared with their predicted positions to estimate pointing deviations. Based on the continuous sequence of star observations, thermal deformation correction coefficients are derived to compensate for thermally induced variations in the instrument's optical pointing direction.

These thermal deformation corrections are combined with attitude and orbit motion compensation to correct the instrument's pointing direction and support real-time image navigation. For the mid-wave (MW) and longwave (LW) infrared channels, the

navigation information is transferred from the visible channel through pre-calibrated inter-channel registration parameters, allowing the geographical locations of infrared observations to be determined.

However, uncertainties in the inter-channel geometric relationship may affect the accuracy of the infrared navigation results. Therefore, the navigation performance of the visible channel cannot directly represent that of the infrared channels, highlighting the need for independent validation using the ground-based laser positioning system (GLPS).

Following the reviewer's suggestion, we have added a description of the GIIRS image navigation method in 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.*"

Question: *I suggest that the authors revise the conclusion section, since the contributions of the work have been already stressed in a dedicated section. Instead, please point out what questions remain unaddressed by the current or what could be done to further improve the performance.*

Our reply: Thank you for this constructive suggestion. We agree that the Conclusion should focus more on the limitations of the current study and potential directions for future research, rather than reiterating the contributions already presented in the Introduction.

Accordingly, we have revised the Conclusion to highlight the remaining challenges and future developments of the proposed ground-based laser positioning system (GLPS). The current study focuses primarily on validating the image navigation accuracy of the GIIRS longwave infrared (LW) channel, while the mid-wave infrared (MW) channel and inter-channel registration accuracy have not yet been independently validated.

Future work will focus on extending the GLPS technique in three directions. First, suitable ground-based lasers and observation stations will be developed to enable independent image navigation validation of the GIIRS MW channel. Second, by combining the independent navigation validation results from the MW and LW channels, the inter-channel registration accuracy between the two infrared channels will be further assessed. Third, the GLPS technique will be extended to the lightning imager onboard the FY-4C satellite to investigate its lightning signal detection and geolocation performance.

These developments are expected to broaden the applicability of ground-based laser validation techniques and provide additional references for evaluating and improving the performance of geostationary satellite instruments.

We have revised Section 6 accordingly to emphasize the limitations of the current study and these future research directions.

"*Future work will focus on developing suitable methods for MW navigation validation and assessing the co-registration accuracy between the MW and LW channels. Multi-station joint observations will also be conducted to improve the spatial representativeness and reliability of the validation results. Furthermore, the GLPS technique will be extended to the LMI onboard the FY-4C satellite to evaluate its lightning signal detection and geolocation performance.*"