Reply on RC1

This study presents the GSV-SRTS model, a novel canopy reflectance model designed for heterogeneous landscapes over sloping terrain by integrating an extended General Spectral Vector (GSV) with Stochastic Radiative Transfer (SRT) theory. The research objective is clear, and the integration of GSV for soil background characterization with SRT theory for canopy representation over sloping terrain represents a meaningful step forward. The experimental design is comprehensive, incorporating both theoretical comparisons with DART and practical validations using the remote sensing observations across different spatial scales. The writing is generally clear, and the study appears to fall within the scope of the journal. However, to further strengthen the manuscript and enhance its impact, several aspects regarding the mechanistic explanation of the model integration, the depth of discussion on certain findings, and the presentation clarity could be improved. The following specific comments and suggestions are provided to assist the authors in refining their work.

Response: We sincerely thank the reviewer for their thorough and constructive evaluation of our manuscript. We greatly appreciate the positive comments. We have carefully considered all the specific points raised. In our revised manuscript, we will address each comment to enhance the paper's impact. We believe these revisions will significantly improve the manuscript, and we are happy to incorporate any further suggestions. Thank you again for your valuable time and insightful guidance.

Point 1: The GSV model is constructed based on the LUCAS global soil database, yet the study area is located in the mountainous region of the northeastern Tibetan Plateau. Please clarify whether this parameterization scheme requires localization adjustments for highly heterogeneous high-altitude areas and discuss the model's applicability in regions with non-European soil types.

Response: Thanks for your kind comment. We sincerely thank the reviewer for this insightful and crucial question, which directly addresses a key aspect of our model's generalizability.

We first clarify that the primary strength of the GSV parameterization lies in its representation of soil spectral variability using a low-dimensional vector space (derived from global data like LUCAS), rather than relying on a single, fixed spectral signature. This inherently provides a more robust framework for different soil types compared to models using a constant soil reflectance. We now discuss that the framework of the model is universally applicable. The requirement is to populate the GSV soil module with spectral endmembers representative of the target region. We did use it. Therefore, the model is directly applicable to non-European soil type regions, provided an appropriate local or regional soil spectral library is used to construct the GSV.

Point 2: Figure 9 shows that the model performs best with high-resolution imagery (Jilin-1). The attribution of this to the model's ability to resolve microscopic details is a reasonable explanation. It is suggested to further discuss: for medium-to-low resolution pixels (e.g., Sentinel-2, Landsat), does the homogenization of internal heterogeneity serve as the primary reason for the decrease in R^2? Does this imply that the model is more suitable for scenes with high intra-pixel heterogeneity?

Response: We thank the reviewer for raising this excellent point, which allows us to refine the interpretation of our validation results and clarify the model's inherent strengths. We have substantially revised the discussion related to Figure 9 and Section 4.4.

Primary Reason for R^2 Reduction: We agree that the homogenization of internal heterogeneity within medium-to-low resolution pixels is a primary, fundamental reason for the observed decrease in R^2, particularly for Sentinel-2 and Landsat. Our model explicitly simulates sub-pixel 3D structure and terrain effects. When the satellite pixel is large, it integrates over a vast area containing multiple terrain facets, canopy settings, and soil patches. While our model can simulate the mean effect, the validation pixel value is a single aggregate, smoothing out the very spatial variations the model details. This mismatch between a high-fidelity simulation of processes and a low-fidelity integrated observation naturally limits the achievable R^2. We have modified the text to state this clearly.

Page 19, Line 411 to Page 20, Line 413:

~~Coarser resolution images tend to smooth out small-scale features, limiting the ability of the model to leverage its detailed photon-tracking capabilities. In contrast, high-resolution images preserve the finer details, more complex and heterogeneous conditions need to be considered in model development.~~ In contrast, coarser resolution images tend to smooth out small-scale features, limiting the ability of the model to leverage its detailed photon-tracking capabilities. This limitation is clearly evidenced by the lower R^2 values obtained with Sentinel-2 and Landsat 9-OLI data, which are primarily attributed to the homogenization of intra-pixel spatial details—terrain variation, canopy structure, and soil background—during the pixel integration process. Our model simulates these sub-pixel heterogeneities explicitly, but the validation data from medium-resolution sensors represents an aggregated average. This does not diminish the model's utility for coarser resolutions; rather, it highlights that the GSV-SRTS model is particularly advantageous for applications where understanding or quantifying the impact of sub-pixel heterogeneity is essential, such as in scaling studies, high-fidelity scene simulation, or informing the parameterization of larger-scale biogeophysical models. As a result, the GSV-SRTS model achieves optimal accuracy with high-resolution images, producing more realistic reflectance estimates. Therefore, the integration of high-resolution data with the photon-sensitive framework of the GSV-SRTS model enables precise capture of subtle canopy reflectance variations, optimizing model performance and achieving highly precise results.

Point 3: In the Introduction, when discussing the limitations of previous models, the phrasing could be more neutral. For instance, changing "these CR models overlooked the impact..." to "these models could be further enhanced by incorporating the impact..." would reflect a more constructive tone.

Response: We thank the reviewer for this important stylistic suggestion, which improves the academic tone and constructiveness of our writing. We have carefully gone through the entire Introduction section and revised the phrasing when discussing the limitations of previous work. Following the reviewer's example, we have replaced more critical phrasing (e.g., "overlooked," "neglected") with more neutral and constructive alternatives such as "could be further enhanced by incorporating...", "have often simplified...", or "not fully considered". These changes maintain the critical point about research gaps while framing our work as a logical progression built upon prior efforts.

Page 1, Line 11-12:

Despite the development of numerous canopy reflectance models for sloping terrain, the heterogeneous characteristics of soil-canopy objects have often been ~~overlooked~~ simplified, leading to distortions in the bidirectional reflectance distribution in small-scale landscapes.

Page 20, Line 437-438:

Although the GSV-SRTS model incorporates terrain effects, the influence of the surrounding terrains was ~~neglected~~ not fully considered.

Point 4: Some long sentences could be appropriately split to improve readability. For example, the long sentence in the Abstract spanning lines 10-12, "However, terrain relief...landscapes," contains multiple clauses and could be considered for segmentation.

Response: We appreciate the reviewer's attention to readability. We have thoroughly reviewed the manuscript, with special attention to the Abstract, Introduction, and Discussion sections, and have broken down several overly complex sentences. The specific sentence in the Abstract has been revised.

Page 1, Line 10-13:

~~However, terrain relief can introduce significant uncertainties into forward radiative transfer modeling. Despite the development of numerous canopy reflectance models for sloping terrain, the heterogeneous characteristics of soil-canopy objects have often been simplified, leading to distortions in the bidirectional reflectance distribution in small-scale landscapes.~~ However, terrain relief introduces significant uncertainties in modeling CR by modulating solar and viewing geometry and exacerbating landscape heterogeneity. Conventional CR models, designed primarily for flat and homogeneous landscapes, often inadequately represent these complex interactions.

Point 5: The captions for Figures 3 and 4 already include clear descriptions for subpanels (a) and (b). It is recommended that all figure and table captions throughout the manuscript maintain this consistent style to ensure uniform formatting.

Response: Thank you for pointing out this inconsistency. We have standardized all figure and table captions throughout the manuscript. Each subpanel (e.g., (a), (b), (c)) is now explicitly described in the caption in a consistent format, mirroring the clear style originally used in Figures 3 and 4.

Point 6: The overall formatting of the references is standard. It is advised to check if the author name format in individual entries (e.g., "Bruno Combal, H. I., and Craig Trotter: ...") conforms to the journal's specific requirements, ensuring consistency across all entries.

Response: We have meticulously checked and reformatted the entire Reference list to ensure strict consistency with the journal's prescribed style guide. The entry noted by the reviewer has been corrected. We have verified author names, journal abbreviations, use of italics, and punctuation in all references.

Point 7: The titles for Sections 3.3 and 3.4 are currently identical. It is suggested to revise one of the titles based on their content; for example, changing the Section 3.3 title to "Assessment of the Canopy Structure Effects on Multi-angle CR Simulations" would make it more specific.

Response: We apologize for this oversight and thank the reviewer for the excellent suggestion. We have revised the title of Section 3.3 to "3.3. Assessment of Canopy Structural Effects on Multi-angle Reflectance". This accurately reflects the section's content, which analyzes the impact of LAI, leaf angle, and canopy cover variations, distinguishing it from Section 3.4's focus on topographic effects.

Point 8: The current manuscript presents the GSV (soil background) and SRT (canopy transfer) as two relatively independent modules. It is suggested to add a paragraph at the beginning of the model framework section (Section 2.1) explaining the motivation for why and how these two components need to be coupled physically.

Response: This is a key suggestion that significantly improves the conceptual clarity of the paper. We have added a new paragraph at the very beginning of Section 2.1 to provide a clear physical and practical motivation for coupling the GSV and SRT modules.

Page 3, Line 87-93:

The accurate simulation of canopy reflectance (CR) over sloping terrain requires a physically consistent coupling of the soil background contribution with the radiative transfer within the vegetation canopy. The soil background is not merely a static lower boundary but a spectrally variable source of reflected radiation that interacts multiple times with the canopy (e.g., through ground-canopy-ground scattering). In heterogeneous mountainous landscapes, both the soil spectral properties and the canopy architecture vary spatially. Therefore, an integrated framework is necessary. In this study, we couple a Generalized Spectral Vector (GSV) model for the soil background with a Stochastic Radiative Transfer (SRT) model for the canopy. The GSV model efficiently represents the high-dimensional spectral variability of soils, providing the lower boundary condition. The SRTS model, operating within a local slope coordinate system, simulates the absorption and scattering of radiation within a 3D heterogeneous canopy. The coupling occurs physically at the soil-canopy interface: the anisotropic reflectance field from the GSV soil model serves as the upwelling boundary condition for the SRT equation, while the SRT-computed transmission and multiple scattering determine the irradiance incident upon the soil. This bidirectional coupling ensures that the combined GSV-SRTS model captures the integrated effect of variable soils and complex canopies under terrain-modified illumination.

Point 9: The article mentions the use of a local slope coordinate system but could elaborate more deeply on its necessity for solving the radiative transfer equation.

Response: We agree that this critical conceptual point deserved more explanation. In the revised Section 2.2.1, we have expanded the discussion on the local slope coordinate system.

Page 4, Line 115-120 to Page 5, Line 121 to 124

The adoption of a local slope coordinate system (x', y', z'), aligned with the inclined ground surface, is fundamentally necessary to render the radiative transfer problem tractable over slopes. In the conventional horizontal coordinate system, a sloping ground surface presents a moving, tilted boundary condition that vastly complicates the formulation of the extinction coefficient and the boundary conditions for the radiative transfer equation (RTE). By transforming to a coordinate system where the z'-axis is normal to the local slope, the ground surface is redefined as a flat plane ($z' = 0$). This crucial simplification allows the use of a standard volumetric formulation for canopy extinction (where the extinction coefficient is defined relative to the direction of propagation) and enables the application of the stochastic approach for gap probability calculation on this effectively 'level' domain. Consequently, all canopy structural statistics and radiative transfer calculations are performed relative to this local frame, and the effects of terrain are encapsulated in the modified solar and viewing direction vectors within this frame, as defined in Equations (1)-(3).For any given global direction Ω, its corresponding local sun zenith angle $\cos\theta_s$ and local view zenith angle $\cos\theta_v$ are calculated as (Gu and Gillespie, 1998):

Point 10: Equations (5) and (6) introduce a topographic modulation function to modify the scattering phase function. It is recommended to further explain the physical intention behind this operation.

Response: Thank you for prompting us to clarify this important model detail. We have added explanatory text following Equations (5) and (6) in Section 2.2.

Page 5, Line 146-150:

The terrain-induced azimuthal dependence of scattering is characterized by a topographic modulation function (S. Sandmeier, 1997). The modulation function, which depends on the local slope angle and the directions relative to the slope normal, physically approximates the effect of this truncated geometry on the scattering process. It adjusts the standard volumetric scattering phase function to better represent the anisotropic scattering behavior in the vicinity of the sloping ground boundary, where the hemispherical distribution of scatterers is asymmetrically constrained. It is described as follows.

Point 11: The article addresses the effects of topography on the extinction coefficient (Equation 4) and the gap probability (via PCF) separately. It is suggested to briefly relate these two aspects in the Discussion section.

Response: Excellent suggestion. We have added a connecting sentence in Section 5 to explicitly link these two physically interrelated aspects.

Page 21, Line 479-487:

The topographic influence on canopy reflectance is channeled through two primary, interconnected physical mechanisms in the model: (i) the modification of the effective extinction coefficient due to changes in the relative pathlength through the canopy per unit vertical depth in the local slope coordinates, and (ii) the alteration of the canopy gap probability, modeled via the PCF within the stochastic framework, which is sensitive to the terrain-modified illumination direction. The first governs the bulk attenuation of direct radiation along its path, while the second determines the probability of direct beam penetration to the soil or lower canopy layers. These two effects are not independent; the altered pathlength directly influences the spatial statistics that underpin the gap probability calculation. Our integrated approach through the local slope coordinate system ensures both effects are consistently accounted for, providing a more complete representation of terrain role in mountain canopy radiative transfer.