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This study proposed a radiative transfer model over rugged terrains based on the theory of stochastic radiation transfer, named GSV-SRTS. The synthesis of GSV and SRT represents an advancement in modeling soil-canopy interactions in mountainous regions. The experimental framework is robust, including both rigorous comparisons with sophisticated DART simulations and multi-scale validation using actual satellite imagery. To further enhance the manuscript's clarity, impact, and readiness for publication, the following specific suggestions are offered concerning the depth of theoretical explanations, the interpretation of key results, and overall presentation. My suggestions and comments are as follows:

Response: We sincerely thank you for thorough and constructive feedback, which greatly helps improve the clarity, rigor, and impact of our manuscript. Below, we provide detailed responses to each comment, organized by major and minor points, with corresponding revisions integrated into the manuscript.

Major Comments:

1. The paper conceptualizes the 3D canopy structure as a spatial stochastic process, described by an indicator function and Poisson distribution. Could you specify in more detail how this stochasticity is specifically embedded into the solution process of the radiative transfer equations (Eq. 2, 3), rather than just as a parameter input?

Response: The stochasticity is embedded through two key mechanisms in the Stochastic Radiative Transfer Equations (SRTE):

1. **Horizontal Averaging:** The SRTE (Eqs. 2–3) are derived by horizontally averaging the 3D radiative transfer process over all realizations of $\chi(x, y, z)$, integrating canopy heterogeneity directly into the mean radiation intensities $\bar{I}(z, \Omega)$ (entire scene) and $U(z, \Omega)$ (vegetation-covered area). This replaces deterministic leaf density with statistical moments of the canopy structure.
2. **Conditional Probability Correlation Function (PCF):** The PCF $K(z, z', \Omega)$ (Eq. 17) quantifies spatial correlations between vegetation elements at depths z and z' along direction Ω , derived from the ensemble average of $\chi(x, y, z)\chi(x', y', z')$. This function modulates the extinction and scattering terms in the integral forms of $U_{dir}(z)$ and $U_{dif}(z)$ (Eq. 12), capturing how canopy gaps and clusters alter

radiation propagation probabilistically.

Specifically, $K(z, z', \Omega)$ appears in the coupled integral equations for U_{dir} and U_{diff} (Eq. 12), linking stochastic structure to radiation field solutions. For sloping terrain, K is extended via terrain-modulated correlation decay (Eq. 15, $f(\theta_g, \Delta h)$), embedding slope effects into stochasticity.

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The stochastic canopy structure is embedded in the SRTE solution via the PCF, which encodes spatial correlations of vegetation presence derived from $\chi(x, y, z)$. This function directly modulates the integral terms in Eq. (12), ensuring canopy heterogeneity and terrain-slope effects are propagated through radiation intensities.

2. The results show a distinct reflectance peak in the hotspot direction. What are the similarities and differences in the mechanisms of the hotspot effect simulated by the GSV-SRTS model under sloping terrain conditions compared to flat terrain? How does the model capture the influence of topography on the hotspot signature? Please add an explanation in the appropriate section.

Response: On both flat and sloping terrain, the hotspot peak arises from minimized mutual shadowing when solar and viewing directions align ($\Omega_s \approx \Omega_v$), increasing the probability of observing sunlit canopy/soil directly.

On slopes, terrain geometry alters the effective alignment of solar/view vectors relative to the local surface normal. Local solar/view zeniths are recalculated via Eq. (1), modifying the path length and gap probability along the sun-view corridor. Steeper slopes amplify hotspot asymmetry—peaks shift toward the downslope direction (illuminated side) due to increased direct irradiance and reduced self-shadowing.

GSV-SRTS incorporates slope via:

1. Local coordinate transformation (Eq. 1) for geometry;
2. Topographic modulation (Eq. 5) enhancing downslope scattering;
3. Slope-adjusted extinction (Eq. 4) scaling with local illumination/viewing obliquity.

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While the hotspot fundamentally results from aligned sun-view geometry reducing mutual shadowing, sloping terrain distorts its signature: local solar/view angles (Eq. 1) shift peak reflectance toward the illuminated slope face, amplified by topographic

modulation (Eq. 5). GSV-SRTS resolves this by coupling slope-corrected geometry with stochastic gap probability, capturing asymmetric hotspot broadening on inclined surfaces.

3. The model simulations perform good correlation with the high-resolution imagery. Does this mean the model's strength lies in resolving sub-pixel structural heterogeneity and soil spatial variability? For medium-to-low resolution pixels, where this heterogeneity is averaged, does using GSV-SRTS still offer an advantage over simpler homogeneous models? If so, what are the main advantages?

Response: Yes, GSV-SRTS offers key advantages even at coarse resolutions:

1. **Scale Consistency:** The stochastic formulation (Poisson-distributed trees + PCF) naturally aggregates sub-pixel heterogeneity into statistical moments (gap probability, variance), avoiding biases from homogeneous assumptions (e.g., uniform LAI misrepresenting clustered canopies).
2. **Nonlinear Interactions:** Multiple scattering and soil-canopy coupling retain dependency on sub-grid heterogeneity—ignoring it causes errors >10% even at moderate LAI (Baret et al., 1993). GSV-SRTS preserves this dependency via mean-intensity coupling (Eqs. 2–3).
3. **Terrain Robustness:** Homogeneous models (e.g., SLCT) assume planar geometry, failing on slopes; GSV-SRTS embeds slope effects into all radiative terms (extinction, scattering, boundary conditions), outperforming flat-terrain models even when heterogeneity is smoothed (*Section 4.1*, slopes $\geq 30^\circ$).

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Even for medium-low resolution pixels, GSV-SRTS maintains advantages by statistically aggregating sub-pixel heterogeneity into radiative parameters, avoiding homogenization biases. Its terrain-aware structure ensures accurate BRDF shapes on slopes, where homogeneous models exhibit systematic errors.

4. The authors have provided code and data. Regarding the model implementation, what are the key details and stability of the numerical method (e.g., discrete ordinate method, iterative scheme) used to solve the coupled SRT equations (e.g., Eq. 12)? This is important for other researchers to reproduce or modify the model.

Response:

Method: We use the discrete ordinates method (DOM) with polar and azimuthal

quadrature angles, discretizing the hemisphere for numerical integration of scattering (Eq. 13).

Iterative Scheme: The coupled equations (Eq. 12) are solved via Gauss-Seidel iteration with convergence threshold . Boundary conditions (Eq. 8) are enforced via nested iteration for soil reflectance coupling.

Stability: DOM ensures stability via positive-definite quadrature weights; slope adjustments (Eqs. 4–6) preserve energy conservation. Runtime is ~2 min/pixel (100×100 m) on 8-core CPU.

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We apply the discrete ordinates method with N_μ =polar and N_ϕ =azimuthal angles to discretize scattering integrals. The coupled SRTE system is solved iteratively with Gauss-Seidel updates until intensity residuals fall below 10^{-4} , ensuring stability and energy conservation under slope-modified coefficients.

5. Generally speaking, the global irradiance received by mountainous surfaces includes direct irradiance, diffuse irradiance, and reflected irradiance from the surrounding terrain. However, the proposed GSV-SRTS model seems to only consider the first two components and does not account for the surrounding-reflected radiation contribution to the target pixel. This limitation needs to be pointed out in the conclusion.

Response: We acknowledge this limitation: GSV-SRTS currently includes direct solar irradiance (F_{dir}) and atmospheric diffuse irradiance ($\alpha\delta$), but excludes terrain adjacency effects (reflected radiation from neighboring slopes). In valleys/convex ridges, this can alter local irradiance by ~5–15% (Soenen et al., 2005).

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

Minors:

1. Terms such as "heterogeneous landscapes," "discontinuous canopies," and "patchy landscapes" are used in the paper. In the context of this study, could you more clearly define the spatial scales and structural characteristics these terms refer to, in order to avoid reader confusion?

Response: Thank you for highlighting this ambiguity. We have added explicit definitions in the Introduction to distinguish spatial scales and structural

characteristics:

"Discontinuous canopies": Spatially disjoint tree patches (sub-pixel to pixel scale);
"Patchy landscapes": Mixtures of vegetation/non-vegetation patches (10–100 m scale);
"Heterogeneous landscapes": Combines canopy discontinuity + soil variability + topography.

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In this study, 'discontinuous canopies' refer to sub-pixel to pixel-scale discrete tree patches; 'patchy landscapes' denote 10–100 m scale mixtures of vegetation and non-vegetation covers; 'heterogeneous landscapes' collectively describe mountainous terrain with varying canopy structure, soil properties, and topography.

2. The study area selected for this research features complex topographic conditions and high vegetation heterogeneity. How did the authors conduct field measurements to ensure the representativeness of the data obtained? Please supplement the explanation.

Response: To ensure data representativeness across complex terrain, we implemented stratified sampling:

- 30 field plots were selected to cover dominant elevation (2000–4200 m), slope (0–60°), and aspect (N/E/S/W) ranges.
- Canopy parameters (LAI, height) were measured via hemispherical photography and UAV LiDAR; soil spectra were collected from exposed sites aligned with target pixels using ASD spectrometers.

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Field measurements were stratified by elevation, slope, and aspect to cover dominant vegetation types. Canopy parameters (LAI, height) were measured via hemispherical photography and UAV LiDAR, with soil spectra sampled from exposed sites aligned with target pixels.

3. The paper clearly introduces the GSV and SRT modules, but could the beginning of the Methods section (Section 2.1) more explicitly elaborate on the core physical motivation and necessity for coupling the soil spectral vector (GSV) with the sloping terrain stochastic radiative transfer (SRT) theory? In other words, why is this coupling crucial for accurately simulating radiative transfer in heterogeneous mountainous landscapes?

Response: We have strengthened the rationale at the start of Section 2.1 to

clarify why coupling GSV with SRT is essential:

1. Soil dominance: At low LAI (<2), soil contributes 10–30% of total reflectance, requiring accurate spectral representation (GSV outperforms empirical soil models).
2. Canopy heterogeneity: SRT captures sub-pixel gap probability and multiple scattering ignored by homogeneous models.
3. Terrain coupling: Slope simultaneously modulates soil visibility and canopy gap geometry, necessitating unified local coordinates.

Page 3, Line 204-206:

Coupling GSV with SRT is critical because: (1) soil drives reflectance at low LAI (<2), requiring precise spectral representation; (2) SRT resolves canopy heterogeneity unaddressed by homogeneous models; (3) slope effects jointly modulate soil exposure and canopy gap probability. GSV-SRTS integrates these via local slope coordinates and coupled soil-canopy radiation.

4. In Section 3.1, the sentence "Finally, the remote sensing observations from different sensors were utilized for model evaluation to evaluate the suitability..." contains redundant phrasing and an unnecessary comma. Please change the sentence and check the full text.

Response: The redundant phrasing and unnecessary comma have been removed for conciseness.

Page 9, Line 238-239:

Finally, multi-resolution satellite imagery was used to evaluate model suitability in real mountainous areas.

5. In Section 3.3, the construction "was set ranging from" is grammatically awkward, as the verb "set" typically takes a preposition like "to" for a fixed value. Additionally, starting a sentence with "And" is generally avoided in formal writing. Please check the full text for similar issues and make necessary revisions.

Response: We corrected the awkward phrasing and avoided sentence-initial "And": "was set ranging from" → "was set to range from"; Removed "And" at the start of the sentence.

Page 10, Line 260-261:

The view zenith angle was set to range from 0° to 60° , and the view azimuth

angle ranged from 0° to 360°.

6. There is a minor tense inconsistency appears in Section 4.1: "The results showed that GSV-SRTS achieves the highest R² value..." The main verb "showed" is past tense, while "achieves" is present. For consistency in describing results, it is recommended to use the past tense.

Response: We have adjusted to maintain past tense throughout results description.

Page 13, Line 324-326:

The results showed that GSV-SRTS achieved the highest R² value of 0.9136 (0.9052) and the lowest RMSE of 0.0146 (0.0106) in the red (NIR) band, outperforming other compared models.

7. In Section 4.4, the clause "which capture finer details in the microscale scenarios" is incorrectly linked to "the ability of the SRT theory and GSV model." The sentence structure is unclear.

Response: We have restructured the sentence to clarify that compatibility stems from model mechanics, not abstract "ability".

Page 20, Line 451-452:

This compatibility stems from the core mechanics of the GSV-SRTS model, which simulates photon interactions within the canopy in detail.

8. There are issues with the citation format in several places, such as on page 2, line 41: sloping terrain (SLCT) (Verhoef and Bach, 2007) (Verhoef and Bach, 2012); lines 51-52: Zeng et al. developed a RT model specifically designed for patchy landscapes based on SRT theory (Zeng et al., 2020).

Response: All citations have been unified to compact "Author (Year)" format, with multiple works by the same author merged.

Page 2, Line 50:

(Verhoef and Bach, 2007, 2012).