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Accounting for Sub-Pixel Variability of Clouds and/or Unresolved Spectral Variability, as Needed, with Generalized Radiative Transfer Theory

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Abstract: Atmospheric hyperspectral VNIR sensing struggles with sub-pixel variability of clouds and/or limited spectral resolution mixing molecular lines. Our generalized radiative transfer model addresses both issues with new propagation kernels characterized by power-law decay in space.

OCIS codes: (290.1090) Aerosol and cloud effects; (290.4210) Multiple scattering; (280.4991) Passive remote sensing.

1. Motivation & Approach

A common tradeoff in hyperspectral sensor design is spatial-for-spectral resolution, to the point where it may no longer be an imager (cf. Fig. 1a). Conversely, in multispectral VNIR/SWIR imager design, SNR and/or sensitivity considerations argue for the inclusion of some or many molecular spectral absorption lines to be mixed in with the scattered and reflected signals and preserve the potentially fine pixel size and broad enough swath (cf. Fig. 1b). Either way, the forward and inverse radiative transfer (RT) modeling used in physics-based retrieval algorithms is challenged. Serendipitous developments in spectral [1] and spatial [2] aspects of RT theory have been unified to address either or both of these issues. This involves however a deep modification of the foundational RT equation (cf. Fig. 1c). In short, averaging Beer's transmission law $T(\ell) = \exp(-\sigma\ell)$ for a *fixed* geometrical path ℓ over the unresolved *variability* of the extinction σ, parameterized by a Gamma distribution [3], leads to $T_a(\ell) = (1+\sigma_m\ell/a)^{-a}$, where σ_m is now the mean extinction and $a = \sigma_m^2/\text{Variance}[\sigma]$. The limit $a\to\infty$ reverts to the usual exponential law.

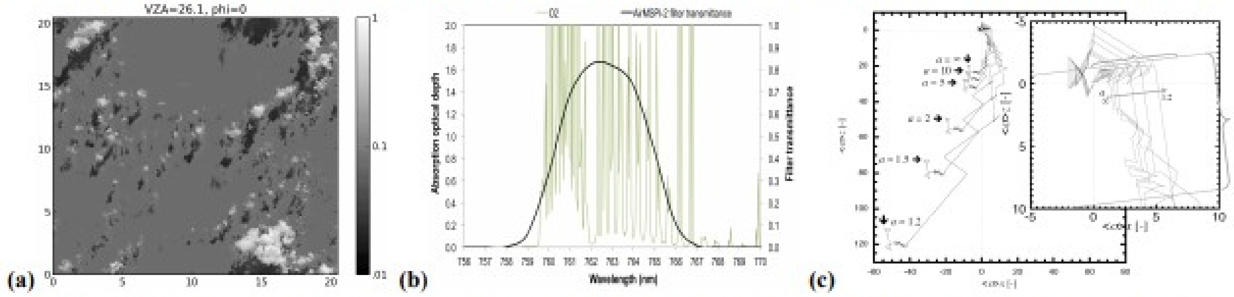

Fig. 1. (a) Possible sub-pixel clouds. (b) Spectral line mixing, e.g., O_2 A-band. (c) 2D Monte Carlo RT with old and new propagation kernels.

2. Standard & Generalized Radiative Transfer Equations (RTEs), and Their Numerical Solution

Let $I(\tau,\boldsymbol{\Omega})$ be *mean* radiance in direction $\boldsymbol{\Omega}$ at *mean* optical depth τ in a plane-parallel medium of total optical depth τ^* (with $\sigma_m = 1$). The RTE in integral form is $I(\tau,\boldsymbol{\Omega}) = \int_{4\pi}\int_{(0,\tau^*)} K(\tau,\boldsymbol{\Omega};\tau',\boldsymbol{\Omega}')I(\tau',\boldsymbol{\Omega}')\mathrm{d}\tau'\mathrm{d}\boldsymbol{\Omega}' + I_0(\tau,\boldsymbol{\Omega})$, where $I_0(\tau,\boldsymbol{\Omega})$ is uncollided radiance and, for simplicity, the surface below is assumed black. Taking single scattering albedo ω and phase function $p(\boldsymbol{\Omega}'\cdot\boldsymbol{\Omega})$ as constant, standard ($a=\infty$) and generalized ($0<a<\infty$) RT models have kernels and sources

$$K_a(\tau,\boldsymbol{\Omega};\tau',\boldsymbol{\Omega}') = \omega p(\boldsymbol{\Omega}'\cdot\boldsymbol{\Omega})\Theta((\tau-\tau')/\mu)|\mathrm{d}T_a/\mathrm{d}\tau|(|\tau-\tau'|/|\mu|)/|\mu| \quad \text{and} \quad I_0(\tau,\boldsymbol{\Omega}) = T_a(\tau/\mu_0)\delta(\boldsymbol{\Omega}-\boldsymbol{\Omega}_0) \qquad (1)$$

where $\Theta(\cdot)$ and $\delta(\cdot)$ are respectively the Heaviside and Dirac functions, $\mu = \Omega_z$, and $\boldsymbol{\Omega}_0$ is incoming solar direction. We show that (1) is efficiently solved numerically with Markov chain methods [2,4], and we illustrate some important characteristics of generalized RT drawing on practical examples in spatial- and/or spectral-domains.

3. References

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