National Aeronautics and Space Administration

Spatially Constrained Retrievals for Imaging Spectrometers

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Background

Current and future imaging spectrometers like AVIRIS-NG, EMIT, and SBG rely on Optimal Estimation (OE) retrievals to extract information about the atmosphere and surface. The retrievals are driven by physics, incorporate a priori knowledge, and include a closed-form estimate of uncertainties. However, the model inversion is ill-posed and many surface and atmospheric features are difficult to disambiguate. Current retrieval algorithms treat each pixel independently, so this ambiguity can lead to biases in atmospheric solutions over certain surface types. Over or under estimation of the atmospheric contribution to the measured spectrum can lead to errors in the applied atmospheric correction, which in turn leads to errors in the retrieved physical quantities that each mission (DELTA-X, FIRE-X, BioSCAPE, EMIT, SBG, etc.) is designed to observe (surface minerology, functional foliar traits, etc.) – many of which are very sensitive to small changes in retrieved reflectance. An obvious solution is to model the interdependence of neighboring pixels, combining information over large areas and solving for a smooth atmospheric field that respects the information provided by each surface type. However, combined solutions are completely intractable since they increase the state vector dimension a million-fold.

Objectives

Our objective is to develop an approach to retrieve scene-wide surface and atmospheric components from imaging spectroscopy data. The proposed algorithm approximates the combined scene-wide solution with a two-step optimization that represents the spatial smoothness of the atmosphere: (1) perform a pixel-wise optimal estimation (OE) retrieval for a subset of pixels that are evenly distributed, using JPL's ISOFIT software package [1] (2) estimate the smooth atmospheric map using Gaussian process regression (GPR), a classical geostatistical approach for probabilistic inference in scalar fields; and (3) perform a second OE retrieval of the surface properties, conditioned on the retrieved atmosphere. We hypothesize that this approach will result in improved atmospheric and surface retrievals since it combines atmospheric information from multiple pixels in the scene, rather than retrieving their atmospheric properties independently. To test our approach, we will validate the retrieved surface and atmospheric parameters with theoretical radiative transfer calculations, as well as AVIRIS-NG imagery collocated with in-situ surface reflectance measurements.

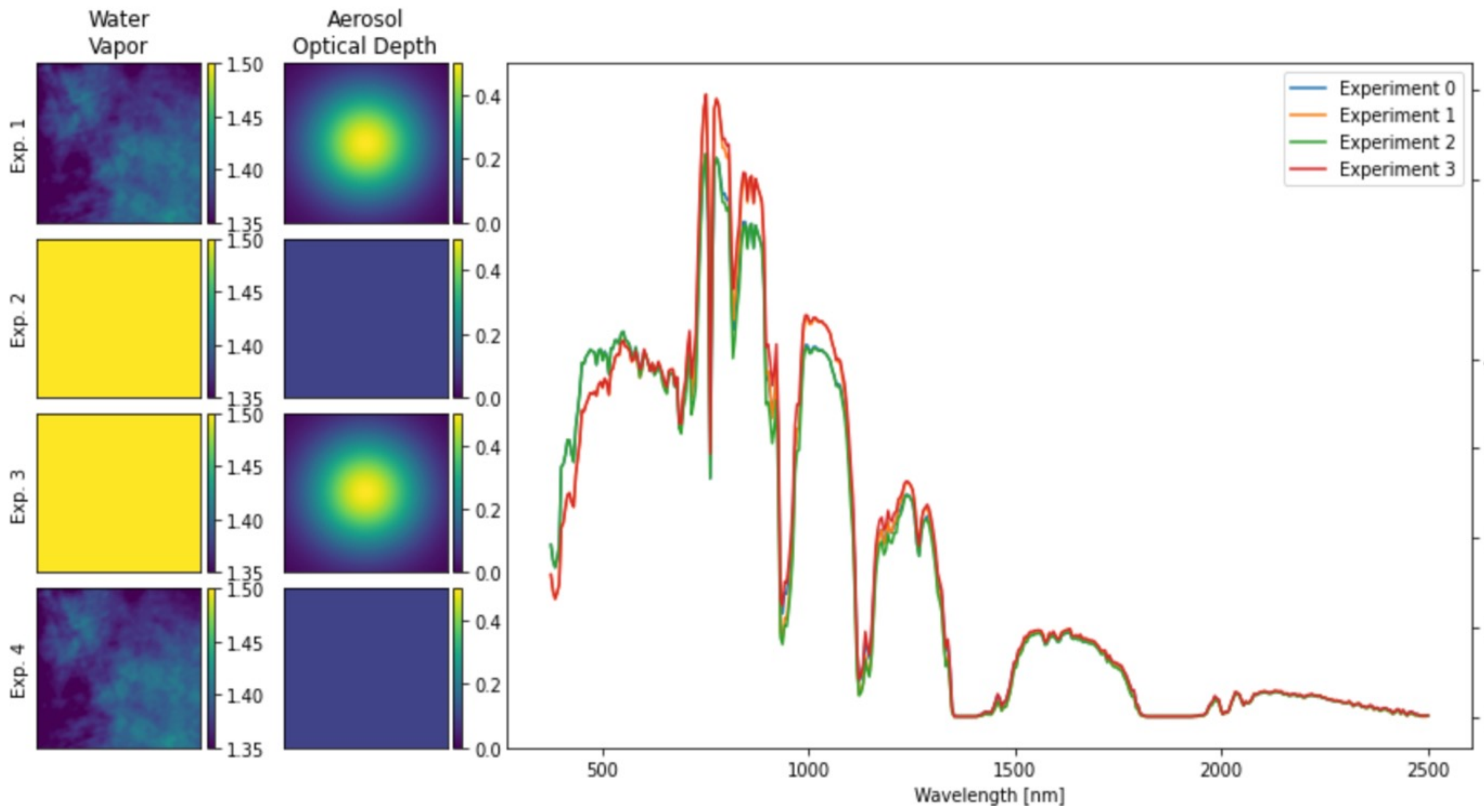

Figure 2. Four different simulation scenarios, each with different atmospheric fields overlain onto a reference reflectance set. The atmospheric aerosol model used for forward modeling differed slightly from that of the model used in subsequent inversions, providing some systematic error to make these test sets reasonable.

Approach and Results

We began by implementing a general form of the multi-step optimization described in the Objectives section. The routine was built around JPL's ISOFIT software package [1] in order to facilitate more direct and immediate use. The algorithm begins by using a PCA / SLIC superpixel segmentation of the scene radiance to decrease the number of direct pixel inversions required [2] with experiments run to determine the maximum possible segmentation size. In the second step, a Gaussian process regression was used to infer the true distribution of the retrieved atmospheric field. Optionally, different terms were included in the GPR kernel to attempt to represent errors due to surface/atmospheric state degeneracy. Finally, a second OE retrieval was performed on a pixel-by-pixel basis, with the atmosphere fixed at the value determined by the GPR.

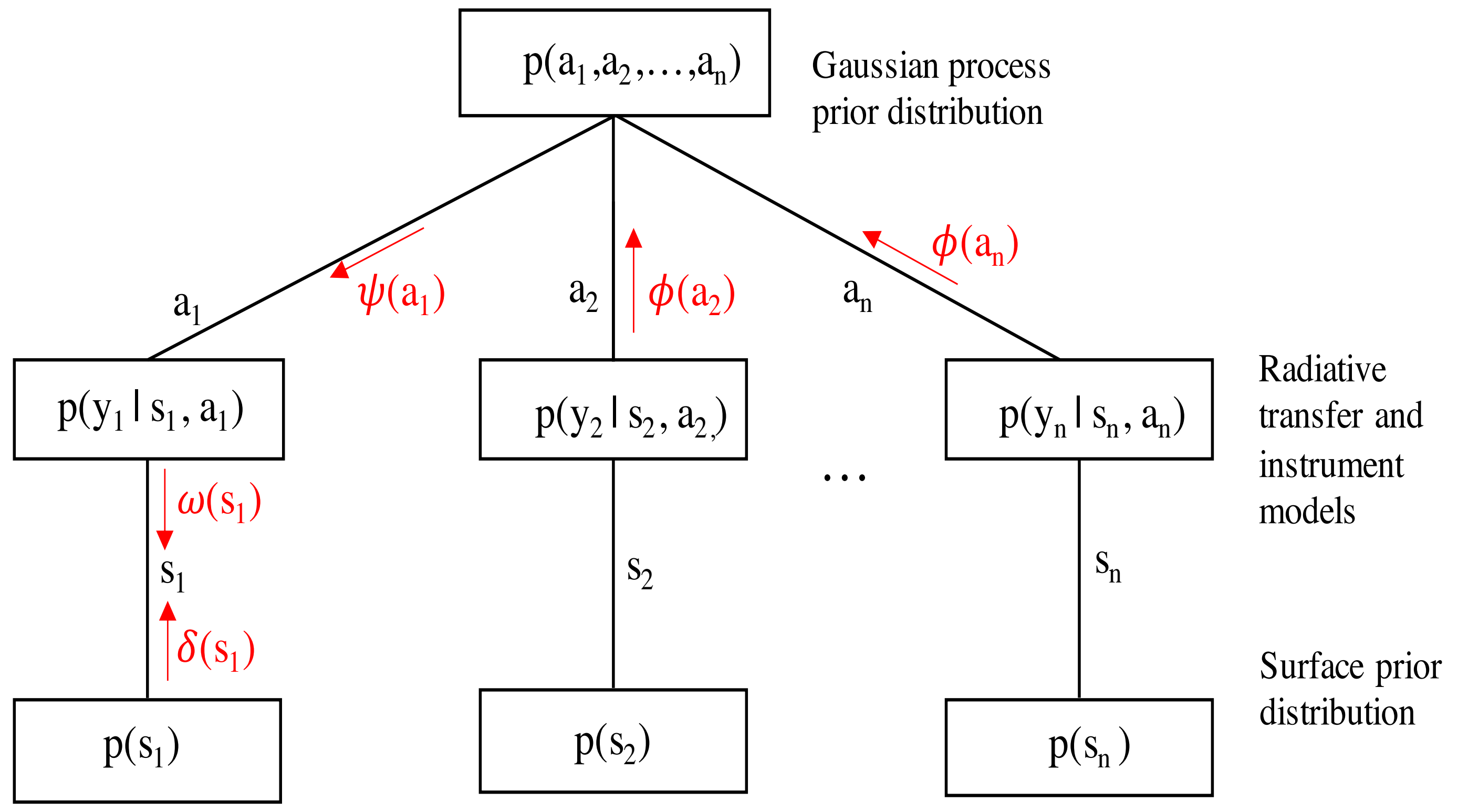

Figure 1. A factor graph of the atmospheric correction problem reveals a noncyclic tree structure. The measurements and surface properties at all locations are independent of each other given the atmospheric state variables, which are tied together via a Gaussian process prior.

Interestingly, this multi-step algorithmic procedure can be shown to be an implemented solution to the complete, scene-wide optimization with coupled atmospheric terms. We do not derive the complete result here, but in brief the joint atmospheric problem can be reformulated as a Forney-style factor graph, with nodes describing the conditional dependence between variables (Figure 1). Because all atmospheric nodes are correlated based on spatial position, but knowing the atmosphere at a certain location results in the surface reflectance and the resulting measurement at that location conditionally independent of all other variables, the marginal distribution of all variables can be calculated efficiently through belief propagation methods.

We demonstrate the efficacy of this approach through a series of experiments, visualized in Figure 2. These consist of four independent atmospheric fields overlain on top of a base reflectance map. To ensure some level of systematic deviation between the simulation and the inversion, the forward model in the inversion used a slightly different aerosol model than was used in the inversion. Next, in Figure 3, we show how the GPR influences the atmospheric field with decreasing superpixel segmentation size. As the segmentation size becomes finer, the heterogeneous water field is increasingly well captured, while the flat aerosol optical depth field is captured well for all segmentation sizes. Some small offsets in absolute magnitude of retrieved aerosol optical depth and water vapor are present in scenes.

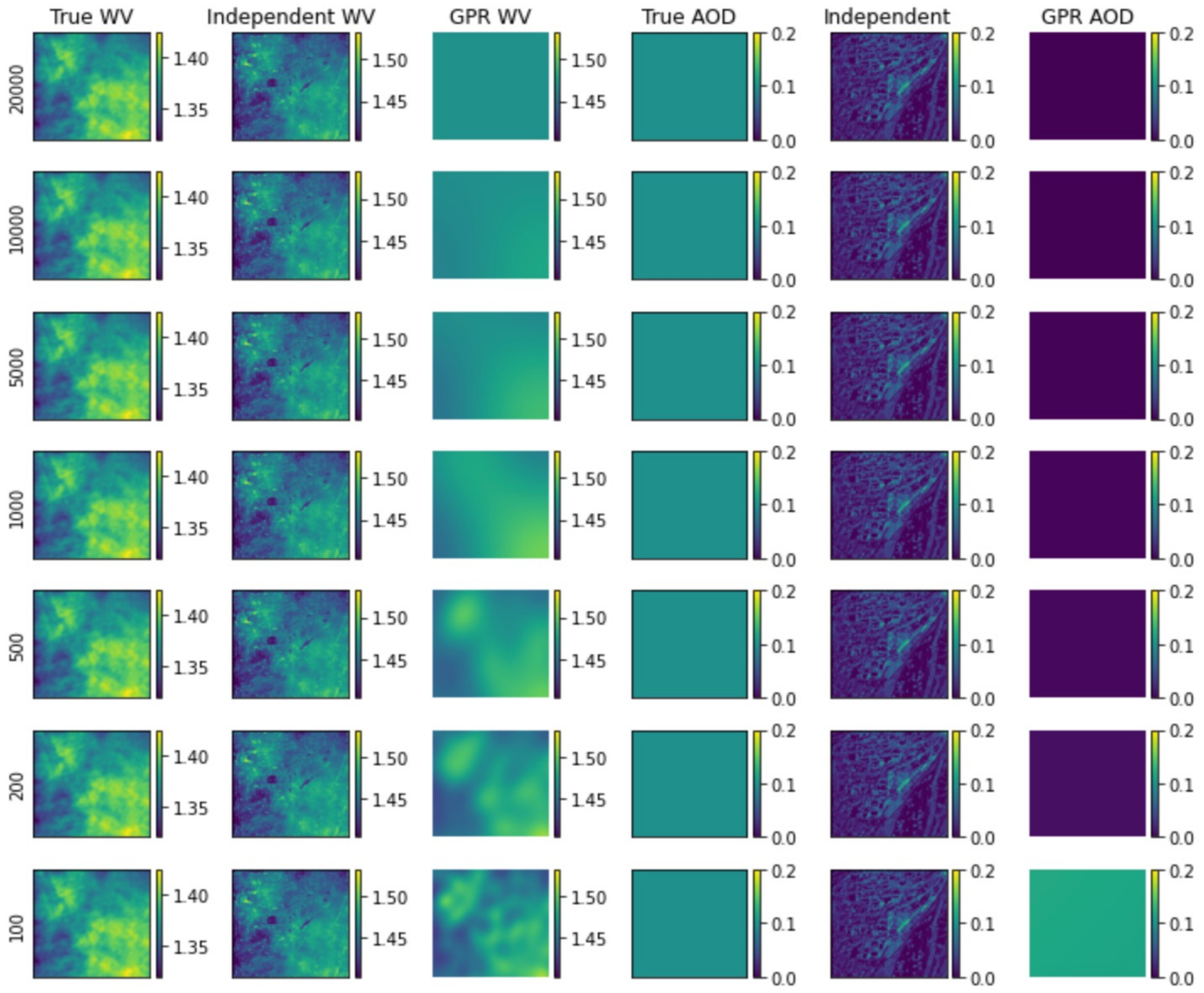

Figure 3. Results comparing the atmospheric fields estimated using the GPR against true and pixel-wise inversion strategies for Experiment 4. Multiple segmentation sizes are compared in different rows.

References

[1] Thompson, D. R., Natraj, V., Green, R. O., Helmlinger, M. C., Gao, B. C., & Eastwood, M. L. (2018). Optimal estimation for imaging spectrometer atmospheric correction. Remote sensing of environment, 216, 355-373.

[2] Thompson, D. R., Braverman, A., Brodrick, P. G., Candela, A., Carmon, N., Clark, R. N., ... & Wettergreen, D. S. (2020). Quantifying uncertainty for remote spectroscopy of surface composition. Remote Sensing of Environment, 247, 111898.

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