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Data Assimilation of Wildfires with Fuel Adjustment Factors in FARSITE using Ensemble Kalman Filtering*

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Abstract

This paper shows the extension of the wildfire simulation tool FARSITE to allow for data assimilation capabilities on both fire perimeters and fuel adjustment factors to improve the accuracy of wildfire spread predictions. While fire perimeters characterize the overall burn scar of a wildfire, fuel adjustment factors are fuel model specific calibration numbers that adjust the rate of spread for each fuel type independently. Data assimilation updates of both fire perimeters and fuel adjustment factors are calculated from an Ensemble Kalman Filter (EnKF) that exploits the uncertainty information on the simulated fire perimeter, fuel adjustment factors and a measured fire perimeter. The effectiveness of the proposed data assimilation is illustrated on a wildfire simulation representing the 2014 Cocos fire, tracking time varying fuel adjustment factors based on noisy and limited spatial resolution observations of the fire perimeter.

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1 Fire Simulations in FARSITE

With the increased and inevitable occurrence of wildfires, modeling and predicting the time progression of a wildfire is important for fire fighting resource allocation to limit the damage of a wildfire. A software widely used by the U.S Forest Service and other federal and state agencies for predicting the time progression of a wildfire perimeter is called FARSITE [1, 2]. Largely based on Rothermel's model [15], FARSITE requires a set of parameters and inputs that describes the topography, fuel, wind and weather conditions where the wildfire is taking place. Based on this data, FARSITE models fire growth via a vector approach and includes fire behavior

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models for surface fire spread [15], crown fire initiation [17], crown fire spread [18] and dead fuel moisture [19, 20].

Despite extensive fire related data collection, fire prediction via direct numerical simulation is imperiled by variability and uncertainty on the data needed to simulate the fire, along with the approximation and empirical modeling of fire spread. Corrections on the wildfire perimeter simulation by means of a data assimilation techniques that can incorporate (noisy) measurements of the actual wildfire perimeter is a promising technique to improve wildfire perimeter prediction. Data assimilation techniques can be found in various wildfire spread models other than FARSITE to improve wildfire perimeter prediction [3, 4]. Merging simulations and measurements of fire perimeters may use Monte Carlo methods [5] to allow for highly large-scale spatial-temporal simulations in a wildfire simulation. Fire spread models may have high dimensional states and include wildfire interaction with the atmosphere [6] where Tikhonov regularization is used to avoid nonphysical states. Some of the most recent data assimilation techniques for wildfire spread prediction [7, 8] rely on an Ensemble Kalman Filter (EnKF) [9–12] also seen in many earth science applications [13].

The use of an EnKF for FARSITE has shown that fire prediction can be improved significantly when intermittent measurements on the fire perimeter are available [14]. However, it has been recognized that FARSITE computations that occur over longer temporal scales may incorrectly predict wildfire spread due to the coarse nature of the spatial and temporal data used in the wildfire simulation [16]. On the other hand, fuel adjustment factors available in FARSITE can adjust the rate of spread for each fuel type independently, allowing compensations of errors and inaccuracy in fuel models, fuel moistures and improperly represented variability in local winds caused by the widlfire.

This paper shows that time varying fuel adjustment factors in FARSITE can be used effectively to fine-tune a fire simulation and address the aforementioned shortcomings. The fuel adjustment factor vector only has a finite dimension determined by the number of fuel models used during the fire simulation. It is shown that any subset of the fuel adjustment vector can be added to the state vector representing the fire perimeter, whereas data assimilation based on the EnKF can be used to update both the fire perimeters and fuel adjustment factors. The data assimilation presented in this paper shows on the basis of a case study of the 2014 Cocos fire in San Marcos, CA that the extra degree of freedom in the data assimilation of fuel adjustment factors greatly improves the accuracy of a fire spread prediction with FARSITE.

2 Forward Model for Wildfire Simulations

In light of the data assimilation techniques presented in this paper, FARSITE can be seen as a dedicated forward-prediction model of the fire perimeter $\hat{x}_{k+1|k}$ of the form

$$\hat{x}_{k+1|k} = f(\hat{x}_{k|k}, \theta, u_k, \alpha_k) \tag{1}$$

in which a distinction is made between spatially varying, but time invaryying, topography and fuel information denoted by a parameter θ, temporal (and spatially varying) wind and weather data denoted by u_k and temporal fuel adjustment factors α_k, where the subindex k refers to a integer time index. The notation $\hat{x}_{k+1|k}$ is used to indicate the predicted fire perimeter at time step $k+1$ based on the data available at time step k. The numerical computations in FARSITE represented by the mapping $f(\cdot)$ in (1) is an implicit and high dimensional forward model.

It should be noted that both the "true" fire perimeter x_k and the fuel adjustment factors α_k are assumed to be unknown. For the purpose of data assimilation and improvement of fire