Recovering Fire Perimeters and Ignition Points of Large Wildfires from Satellite Observations

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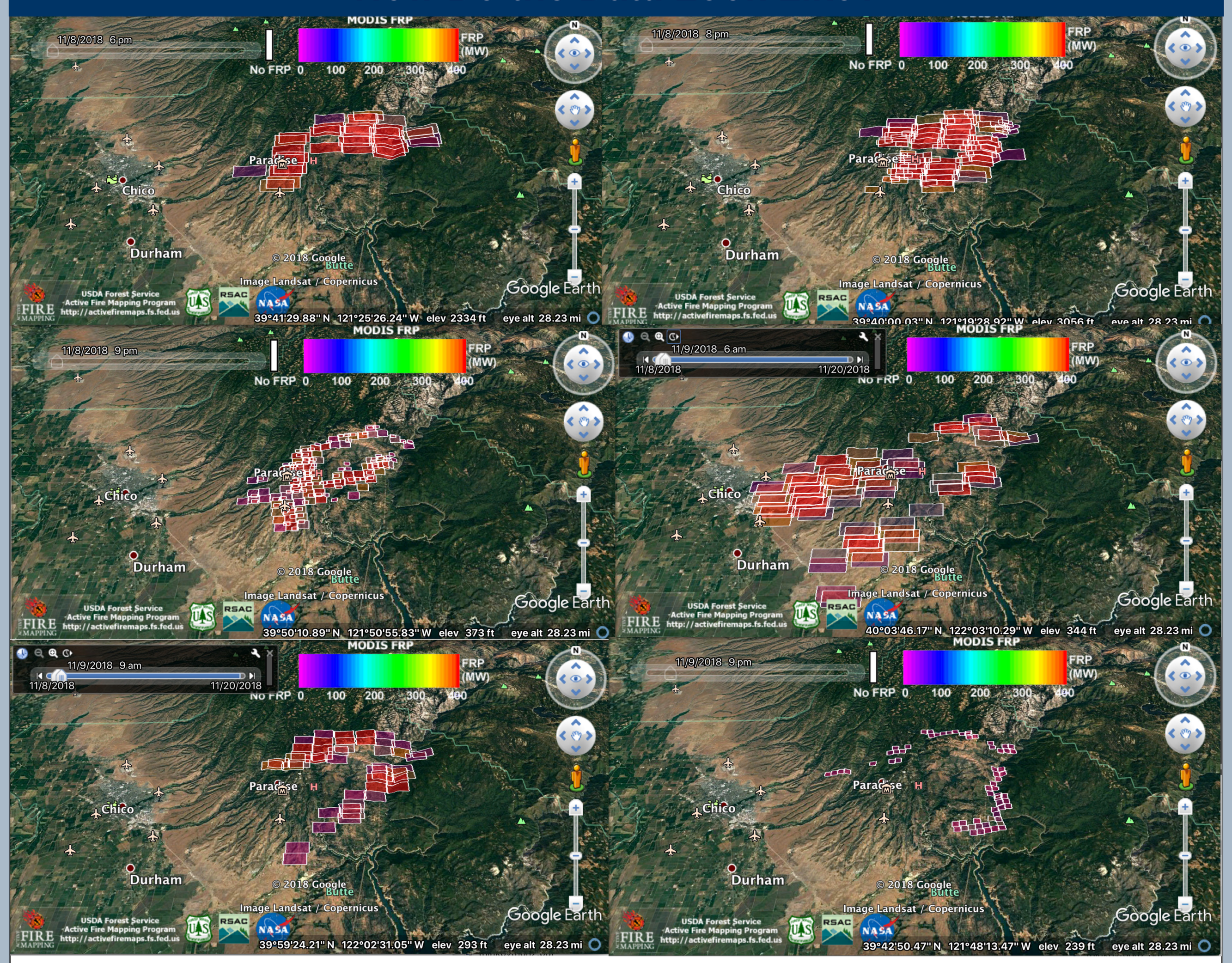
GOAL: Estimate Fire Arrival Time from Satellite Data As a Continuous Spatial Field

- Perimeters = the fire arrival time is constant
- To spin up and assimilate in coupled atmosphere-fire models
- To fill in missing pixels for smoke estimation
- Light-weight, no physics model, statistically justified
- Use all data granules intersecting the domain and time of interest

Unfortunately in reality…

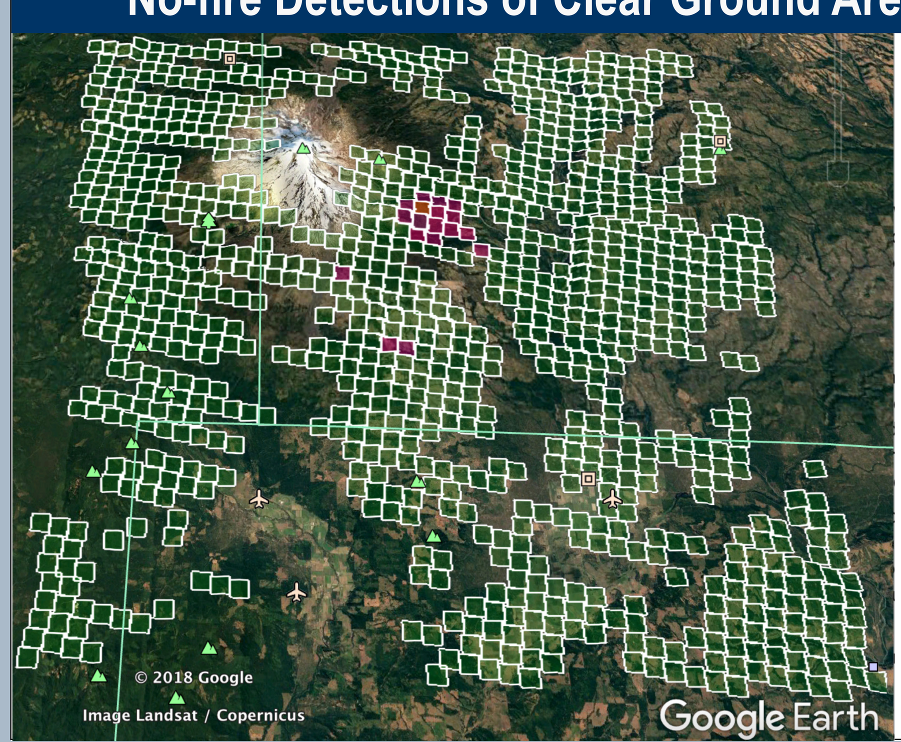
- Data are often missing (clouds, smoke, obscured by terrain,…)
- Pixels do not form a nice continuous progression in time.

How Do the Data Look Like?



Fire Radiative Power in a time progression of sample VIIRS and MODIS granules. Pixel sizes from instrument properties and the scan angle. (2018 Camp Fire)

No-fire Detections of Clear Ground Are Important Too!



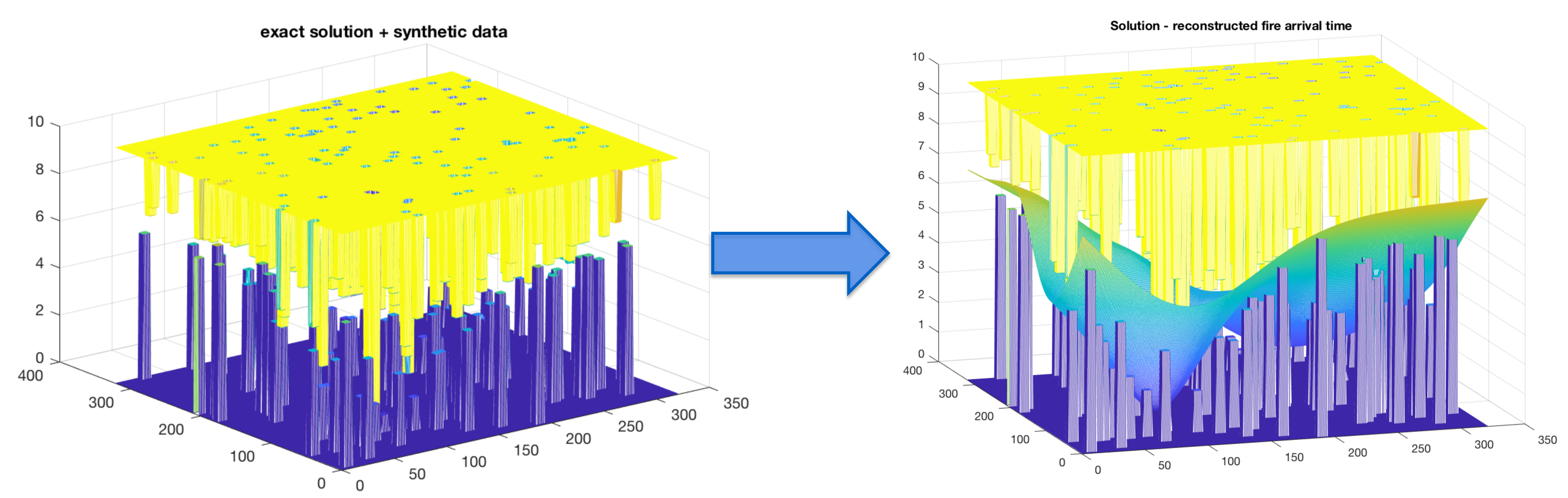
Fire detections in the domain of interest in one MODIS granule.

Green = no fire
Red = fire
Clear = no data

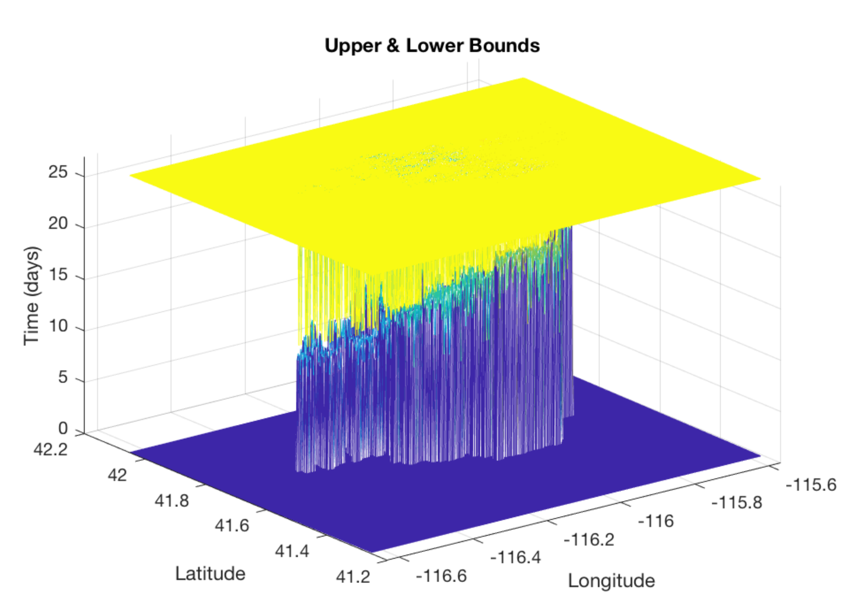
(2015 Cougar Creek Fire)

Basic Method – Ideal Case

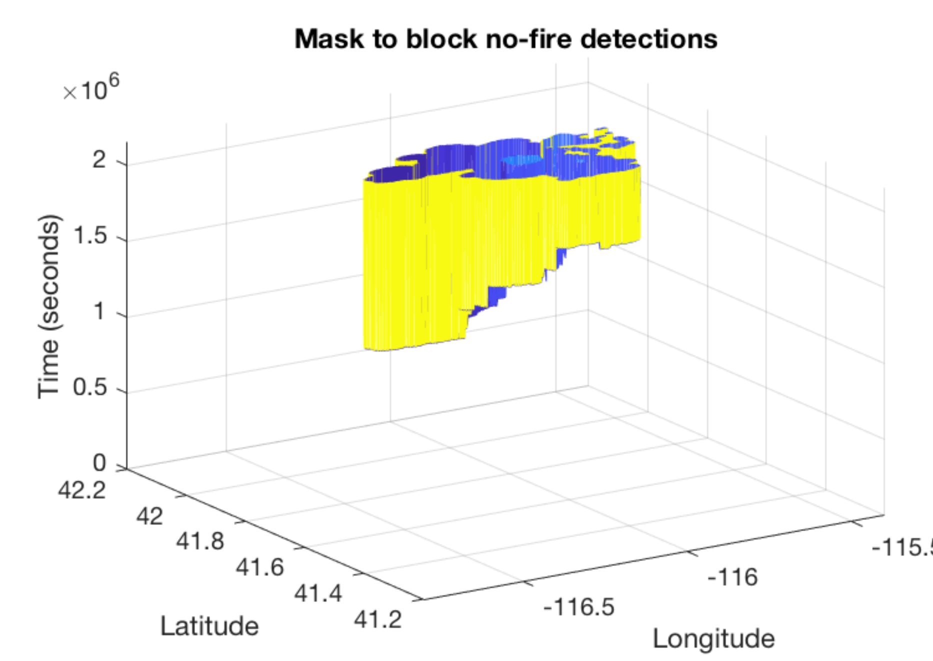
- To fill missing data, assume the fire propagates with the same rate of spread and direction
- Background state: **constant spatial gradient of the fire arrival time** T
- Solve $\text{grad grad } T = 0$ approximately by least squares
- **First fire detection** at a location ⇒ upper bound on the fire arrival time
- **Last detection of ground with no fire** ⇒ lower bound on the fire arrival time
- This is the same as the bending of an elastic plate between an upper and a lower obstacle



Real Data Are More Tricky



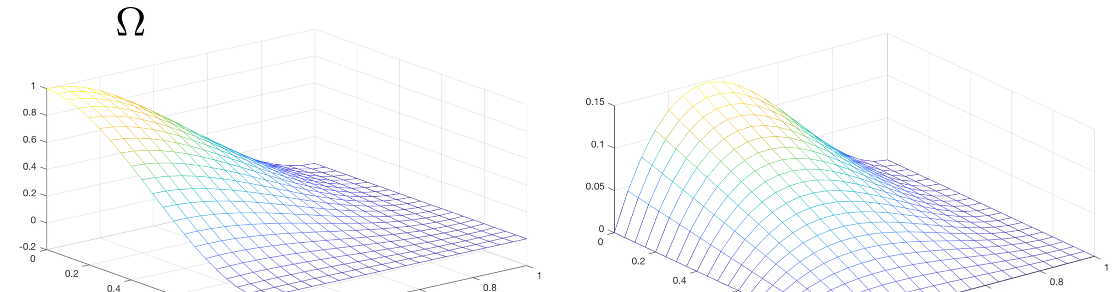
First fire and last no-fire detections (2018 South Sugarloaf Fire)



- Many false negative and some false positive detections ⇒ make the obstacles **soft**, with the lower obstacle even softer.
- After a while, a location with fire detected will give no-fire detections again ⇒ **mask** no-fire detections in future around every fire detection.

The Math

- Variational inequality for the 4th order plate bending partial differential equation: $\int_\Omega \|\text{grad grad } T\|^2 \, dx_1 dx_2 \to \min_{L \le T \le U}$
- The unknown fire arrival time is represented by the Adini element on a rectangular mesh as piecewise cubic functions. The degrees of freedom are the values and the partial derivatives at the mesh nodes:

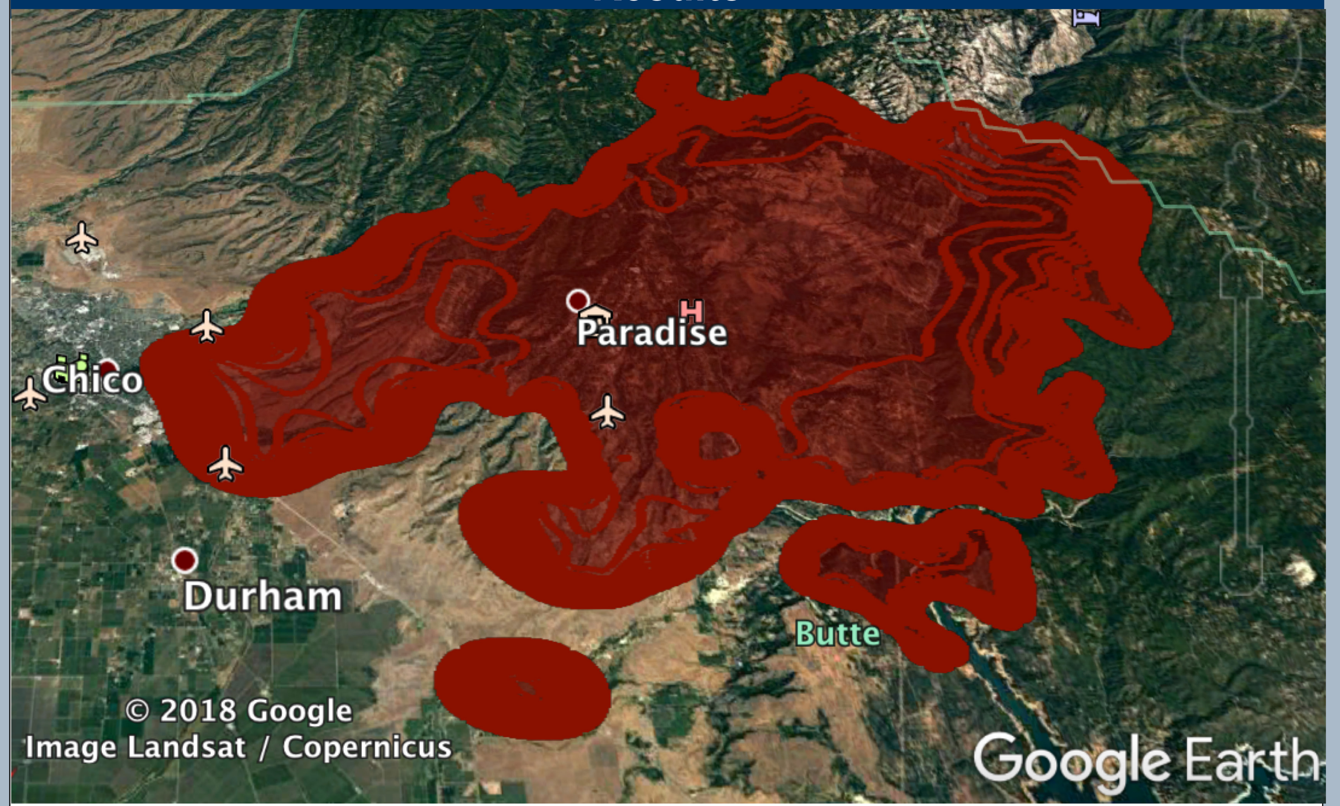


- The discrete penalized problem, solved by a multigrid method:

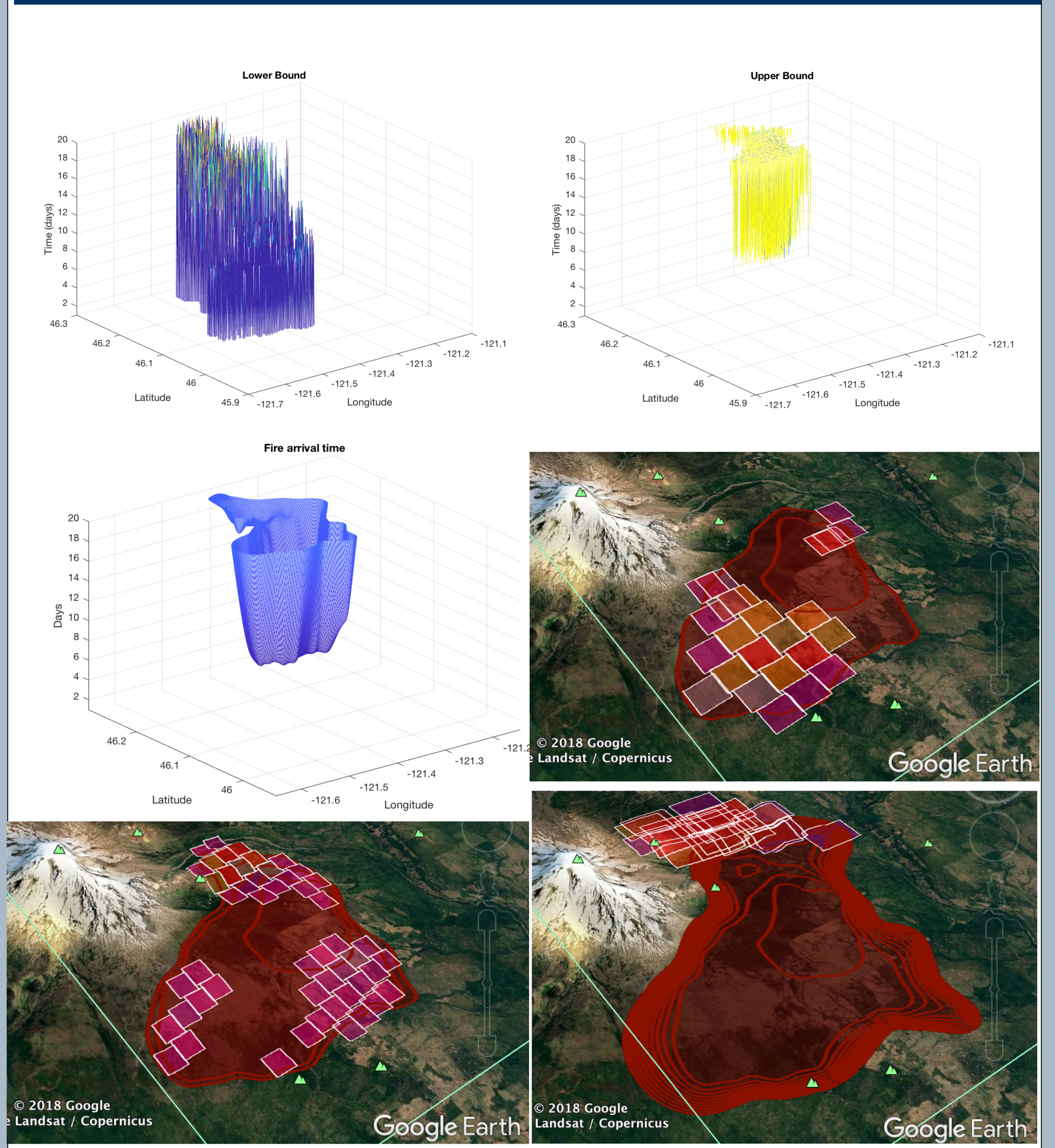
$$\underbrace{\sum_{i=1}^{n}\sum_{j=1}^{n} T_i^T C_{ij} T_j}_{\text{bending energy}} + \underbrace{\sum_{i=1}^{n} a_i^2 \min\{T_{i,1} - L_i, 0\}^2}_{\text{lower penalty = soft constraint}} + \underbrace{\sum_{i=1}^{n} b_i^2 \max\{T_{i,1} - U_i, 0\}^2}_{\text{upper penalty = soft constraint}} \to \min_T$$

- Statistical interpretation: maximum a-posteriori probability Bayesian estimate.
  - Gaussian prior log density equals minus the bending energy, with maximum probability when $\text{grad} T$ is constant.
  - The log data likelihood equals minus the sum of the penalty terms.

Results



Retrieved perimeters of 2018 Camp Fire estimated from VIIRS and MODIS data



Lower bound, upper bound, fire arrival time, and retrieved perimeters with satellite detections at select time points. (2015 Cougar Creek Fire)

Acknowledgements

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