The Physics and Phenomenology of *Wildfire*

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Outline and Research Goals

- We have obtained NASA funding to study the possibility of using inexpensive satellites in LEO as fire monitors:
  - Basic phenomenology of wildland fires
  - Fire scene simulation using our ray-tracing/propagation code DIRSIG
  - Fire detection algorithms
  - Satellite sensor and optics ‘straw man’ designs

- About the Digital Imaging and Remote Sensing Group at RIT
- Ecology, environment, resources and other motivating issues
- What is a wildland fire? - wildland fire behavior and flame physics
  - Laboratory and Field fire characterization experiments
The Digital Imaging and Remote Sensing Group specializes in physics based remote sensing applications and modeling.

- Our programs use physics-based modeling and simulation to study algorithms and remote-sensed phenomena.
- We acquire our own data with an airborne 70-band multi-spectral imager - MISI.
- We have written a physics-based ray trace simulator to model the scene, atmospheric transmission (MODTRAN) and sensor (DIRSIG).
The remote sensing group uses a number of computational and experimental tools.

DIRSIG synthetic imaging simulator

MISI 80 band airborne scanning camera
Motivation for Wildland Fire Research
Wildfires are omnipresent in the natural environment

- Fires affect the global climate through processes such as trace gas and aerosol production, and by changes to terrestrial carbon dynamics.
- Fires consume trees and other forest resources that may otherwise be harvested.
- Fires are a source of severe local air pollution for residents nearby.

- Some tree species and forest ecologies require fire for health and propagation.
- Fire affects predator-prey relations as well as killing many individuals (but populations?)
- Fire has always been a part of the natural environment.
Why study forest fires? Why build orbital fire detectors?

- Correct allocation of fire fighting resources reduces costs, minimizes risk to life and property.
- It is currently difficult if not impossible to monitor wildfires accurately.
- Airborne systems are inadequate because of limited coverage and short loiter time. High-flying airborne systems (U2) are logistically difficult.

Particulate matter, CO, CO₂, methane, evolved water alter atmospheric transport of solar energy.

Atmospheric gaseous composition is incredibly important to energy balance - and life on Earth:

Actual average surface temperature = 288 K --> +34K from greenhouse effect

Radiation

\[ 4 \pi r^2 \sigma T_e^4 = \pi a^2 S (1 - a) \]

Absorption

\[ T_e = \left[ \frac{S (1 - a)}{4 \cdot \sigma} \right]^\frac{1}{4} \]

\[ T_e = 253.622 \]
Do forest fires alter the radiation balance of the earth?

- Antarctic ice samples (and other evidence) show long term increases in several greenhouse gases
Better techniques are required to detect, monitor and combat wildfires

- Current procedures developed over 75 years do not take advantage of the latest technology.

- Knowledge of fire position and spread rate makes resource allocation effective and modeling possible.

- Unusually high spread rates cause the majority of forest fire fatalities.
Forest fires have been detected in the past by observing IR emissions

- Thermal emission spectra from 1200K fire peaks at (Wein displacement law):
  \[ \lambda = \frac{0.29}{T} \text{ (cm)} = 2.4 \mu\text{m}. \]

- Multi-band IR measurements allow approximate determination of temperature of scene

- Long wavelength IR (8 - 12 \( \mu\text{m} \)) can detect fire scars and ‘hot’ ground (if large enough in area)

- Very large dynamic range necessary for MWIR (2.5 - 5 \( \mu\text{m} \)) detectors to avoid saturation

- Likelihood for false alarms is very high if only one waveband is used
IR detection of fires presents difficulties when using simple, low cost systems

- IR detectors typically not as sensitive (on any measure) as visible (silicon) devices
- IR detectors need cooling, in general (bolometers a possible exception)
- Small fires may be important as precursors to larger burns and as predictors of fire spread.
- Small fires, which are in general sub-pixel events in a small-telescope satellite, are indistinguishable from specular reflections.
- A detector only measures the total incident power. For a particular pixel, in a given waveband, the same power can be obtained from a large area high reflectivity warm surface (false alarm) or a cold background + fire (‘true” alarm).
- Distinguishing a fire needs a discriminating condition - which could be obtained by comparison with adjacent pixels, etc.
- A large, hot fire will saturate a detector designed to look at Earth-ambient temperatures (300K)
Wildland fire is a complex physical phenomena that demands multidisciplinary research.
Wildland Fire Behavior and Physics
Wildfire is a dynamic and diverse phenomena.

FIRE TYPES

Most wildland fires are complex blends of ground fire, surface fire, and crown fire.
Fire converts complex hydrocarbons to simpler molecules with the release of heat (1)

- The combustion process (in general) consists of a **pyrolysis cycle** and a **soot cycle**.
- In the **pyrolysis cycle**:
  - Volatile fuel compounds evaporate.
  - Pyrolysis (heat divided) subdivides fuel into 2 - 4 carbon chains. Thermal energy comes from radiated heat from reaction zone.
  - 2-4 carbon chains diffuse into reaction zone and mix with oxygen
  - Oxidation of small HC causes energy release (back-radiated energy causes further pyrolysis)
Fire converts complex hydrocarbons to simpler molecules with the release of heat (2)

- The combustion process (in general) consists of the following steps (soot cycle):
  - Evaporation of volatile fuel compounds
  - Volatile compounds aggregate into (roughly) spheroidal ‘soot’ particles. Molecular weight of these particles is still high.
  - Unburned soot diffuses and circulates throughout the flame interior
  - With emissivity near 1, soot particles absorb thermal energy from reaction zone and re-radiate. Hot soot is responsible for the yellow flame color
Wildfire begins with a pilot ignition source

- Ignition of duff or other fuel initiates a complex chain of reductive reactions.
  - Earth receives $8 \times 10^6$ lighting strikes per day.
- Preheating, flaming, smoldering and glowing combustion produce a diversity of reaction products.
- Pre-ignition dehydration in wildland fuels occurs as the pilot heat dries (removes) water in the fuel.
- Fuel cloud formation follows with continued pilot heat. Fat, oils, turpene, alcohol and resin molecules form a fuel cloud.
Ignition and combustion follow application of pilot heat

- Persistent pilot heat scorches the fuel, producing char that emits a thick, gray tar smoke. (cellulose pyrolysis)
- The fuel cloud mixes with oxygen in the air and burns independent (exothermically) of the pilot heat.
- Radiant heat form the reaction zone preheats and ignites previously cool wood surfaces.
The now self-sustaining process continues from flaming through glowing phases.

Flaming combustion produces radiant thermal energy which preheats the remaining fuel. FC continues until volatiles are exhausted.

After complete cellulose pyrolysis to char and tar, the fuel cloud grows smaller. The flame tent collapses.

The collapsing reaction zone travels to the fuel and combustion continues in the glowing phase. The char (basically C) burns with a blue flame producing CO$_2$ and CO.
Modeling the spread of wildfire is complex

- The location and spread rate of the fire is the most important information from a fire-fighting perspective.

- Accurate models are available (USFS FARSITE) but these models are only as good as weather, terrain and fuel type input data.

- Models are 'tweaked' during run using known position of fire (if available)

FARSITE fire propagation model - point source ignition, one hour fire front contours
Fire Experiments and Field Data Collection
We have conducted laboratory experiments to provide data for input to our simulations

- We need to understand the basic physical phenomena in a fire that govern the gross behavior

- We need to know what simplifications and assumptions can be made to ease calculations required for image synthesis and modeling

- We need to be able to analyze and predict the emission of narrow spectral features from wildland fires

- We definitely need, at a minimum, the emissivity and temperature profiles of the flames to model a fire with DIRSIG
The experiments were conducted in the combustion chamber at the RMSC in Missoula Montana

- The burn surface of the chamber is about 10 m square
- The smoke stack of the burn chamber is about 40 m high
- The ‘draw’ from the combustion chamber is assisted by a 25 hp fan

In-situ instrumentation includes combustible material mass, CO$_2$, chamber temperature

- An aluminum fire bed (0.91m X 2.43m) was used. A gauge grid (0.3m) was present to judge the location of the fire.
Our goal was to **extensively characterize optical emissions from several wildland fire materials**

- Make definitive spectral measurements of laboratory-condition controlled fires --> *Wideband measurements not available*

- Correlate narrowband spectral features with broadband (blackbody) features ---> *Little or no high resolution characterization in visible bands (1-3 nm FWHM resolution)*

- Determine emissivity of flames and the fuel bed ---> *Emissivity not known, some anecdotal information*

- Develop a shape library and/or methodology for local, detailed spatial rendering of flames --> *Even Hollywood can’t do this modeling!*

- Make other discoveries (alkali number density in flame, temperature, etc.) based on quality of the data. ---> ????
We measured a broad range of spectral and physical data during the experiments.

Yellow - RIT instrument
White - USFS instrument

USFS IR Radiometer Filter Bandpass (in microns)
1. 2.44 center, 0.47 FWHM
2. 4.04 center, 0.55 FWHM
3. 5.71 center, 0.90 FWHM
4. 6.70 - 10.69
5. 7.355 center, 1.75 FWHM
6. 10.6 center, 2.4 FWHM

Ocean Optics Spectrometer
Ch1: 190 - 374 nm
Ch2: 640 - 1280 nm

Heitonics KT19.8
IR Radiation Pyrometer
10 - 12 µm

ASD Fieldspec FR
VIS/NIR Spectrometer Platform
0.4 - 2.5 µm
We have one absolute and several relative spectral measurements. We may be able to infer emissivity, temperature, and other relevant flame physical parameters.
Across track videography measures the (visible and IR) spatial extent of the fire and fire ‘temperature’

- A Sony digital video camera are used to record the visible emissions form the fire (manual exposure + ND filter)

- An Inframetrics-600 (FLIR) records the IR emission in the 10-14 μm waveband

- A Sony digital video camera records the video stream from the Inframetrics IR video camera (set to 1000K span and 325K lower limit)
High-speed visible videography was acquired along-track

- A JVC digital video camera can capture ~120 frames per second in a sub-sampled mode.
- The camera viewed the fire along-track, opposite from the ASD FieldSpec spectrometer.
Across-track IR Videography is being analyzed to measure cooling rates of fire ‘blobs’, emissivity, and temperature profiles.

- With some assumptions about the incandescent particulate smoke components, we can measure the cooling rate of particulate clumps that are evolved.
- The volume of the fire at any time can be measured.
- The size distribution of the particulates is known (C. Hardy, D. Ward, RMRS).
- The cooling rate can be modeled: Do we understand the emissivity and composition of the particles?

3-Band Visible Videography

IR (8-14 µm) Videography
Spectrometers span the 0.35 - 10.6 μm wavelength regime

- **ASD Fieldspec FR spectrometer:**
  - 3 nm FWHM spectral resolution
  - 3° field of view
  - 0.35 - 2.5 μm spectral range

- **Ocean Optics**
  - 0.365 nm FWHM spectral resolution
  - Spec1: 0.64 - 1.28 μm
  - Spec2: 0.18 - 0.875 μm
  - 10° field of view

- **RMRS Filter Spectrometer**
  - 6 channel: 2.44, 4.04, 5.29, 7.35, 10.6 μm + wideband (0.2 - 30 μm)
  - 10° field of view

Stef VanGorden beating the ASD into submission
An ASD Fieldspec FR and an Ocean Optics D2J provided high resolution VIS-NIR spectra

- We have very good high resolution spectra in the visible (0.3 - 0.9 μm).

- The NIR - MWIR is currently not as well understood. Are we having ASD problems? Is the ASD capable of making wide dynamic range radiance measurements?
A USFS-constructed 5-channel filter spectrometer measured the 2.4 - 10.6 μm emission.

- Data reduction and recalibration in progress
- Overlaps with ASD (2.44 μm)
- Attempt to observe spectrum in the LWIR to measure departures from Planckian shape
The particulate smoke and tar emit a blackbody spectrum

- The high molecular weight tar components effectively are gray bodies, are heated by the radiation field from the combustion process, and emit in the infrared (2 - 8 μm peak)
- We have obtained reasonable estimates of the packing fraction of these particles in the fire bag.

![Graph showing exitance in the 8 - 12 micron waveband](graph.png)

The high molecular weight tar components effectively are gray bodies, are heated by the radiation field from the combustion process, and emit in the infrared (2 - 8 μm peak). We have obtained reasonable estimates of the packing fraction of these particles in the fire bag.
We have discovered very interesting narrow-line features during wildland combustion. We have detected narrowband emission lines from potassium, sodium and phosphorous. These elements are major constituents by weight of plant fuel material. The potassium emission feature is very strong because of low ionization potential and high abundance.
Vegetative biomass is primarily composed of just a few elements

- As expected, most of the mass is H, C, O and N (by weight):
  - C: 45%
  - H: 5.5%
  - O: 41%
  - N: 3.5%

- But there are large (and varied) weight percentages of ‘trace’ elements:
  - K: up to 7%
  - Na: 0.1%
  - P: up to 1%
  - Ca: up to 5%

- Some of these elements have unique spectral properties in a fire
We have analyzed an AVIRIS fire data sets in several wavebands (Cuiaba, BZ)

- Individual pixels of this data show strong potassium lines
- Some IR channels saturated

![Spectra of Fire & Background in AVIRIS Scar-B Data](image)
We have analyzed an AVIRIS fire data sets in several wavebands (Cuiaba, BZ) (2)

- A - 589 nm - no smoke penetration
- B - 770 nm - smoke penetration, bright active fire fronts visible
We have analyzed an AVIRIS fire data sets in several wavebands (Cuiaba, BZ) (3)

- C - 1500 nm (smoke penetration, fire fronts)
- D - Band ratio, 769 nm / 779 nm thresholded to 6 σ
Very strong emission features from gaseous fire products in the VIS/NIR have been recorded.

- Features from hot CO$_2$ and H$_2$O dominate the molecular emission spectrum.
- This spectrum was obtained from wet fuel material (Doug. Fir) in the smoldering combustion phase.
- Even though the atmosphere absorbs strongly in these bands, the possibility of ‘edge effect detection’ from thermal broadening is exciting.
We have performed field data collections at 3 controlled burns in the northeast.
We acquired spectra and ground cooling rates at a controlled burn at Ft. Drum (NYS)

We observed a 125 ha controlled burn at Fort Drum (Watertown, NY)

The burn is used to control undergrowth to ease troop movements

We did not overfly because of logistics difficulty with attack aircraft and artillery

Fire fighters from Ft. Drum (USA), USFS (GMNF and FLNF) ran the fire operation
At a controlled burn at Finger Lake National Forest, we obtained both ground and airborne-instrument data.

We used the ASD spectrometer to measure spectra of the fire and reflectance of the burn scars.

The MISI hyperspectral camera was overflown in a Piper Aztec at 1000, 1500 and 2500 m.
Airborne instrument overflights successfully captured thermal and narrow-band fire features.

Zoom of fire area from false-color image. Red pixels are high-value potassium emission (flaming combustion).

Thermal image from same scene, showing hot burn scar and combustion front. Hot gases evolved from combustion are to the lower right.

MISI false-color image (766 - 756 - 776 nm)
Managing Forests and Forest Fires
Forest and forest fire management has changed significantly over the last 100 years

- Initial response to fires in the US was to ‘let burn’ (until 1886).
- Yellowstone Park fire of 1886 was controlled by the Army.
- US Forest Service established in 1905 by Teddy Roosevelt. Gifford Pinchot, conservationist and forester, was first head.
  - Pinchot established a program of research, production and control based on European models of silviculture. Fire was to be combatted at all costs (a fire is a waste of wood!)
- ‘10 AM’ established in 1920’s. CCC became part of the fire fighting workforce.
- 1940’s - some fires discovered to be beneficial to pine plantations in the South.
- 1960’s - beneficial effects and necessity of fire became apparent
- 1990’s - limited ‘let burn’ policy instituted, if life and property not at risk.
Forest fires a battled by a complex multi-faceted organization

- Depending on the size and danger of the fire, a flexible response may be mounted to combat the blaze.
- The ‘Incident Command’ hierarchy is used. This management tool is common to FEMA, armed services, and NGOs.