Aerial Imaging and Tracking of Gases Entrained in Biomass Burning Outflows

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Abstract

Aerial remote sensing investigations of several wildfires occurring in the U.S. states of California and Oregon were mounted in 2019-2020. Such measurements provide a link between the microscale chemical-dynamic processes in wildfire outflow plumes obtained by in situ sensors and the macroscale transport information derived from space-based instrumentation, thus filling an essential role in efforts to characterize wildfire-driven teleconnection processes. Correlated, quantified measurements of wildfire co-emissions were obtained with a wide-swath longwave-infrared airborne imaging spectrometer with the species observed including ammonia, ethene, nitrous acid, methane, methanol, and acetic acid.

Introduction

The increasing incidence and severity of biomass burning (BB) events pose a multidimensional threat impacting economic resilience, national security, and public health. Consequently, growing attention has been devoted to the radiative and chemical effects of BB gas and aerosol emission into the atmosphere, as well as the accompanying effects on human health. The emphasis of the work reported here concerns the efficacy of airborne spectral imaging in the longwave-infrared (LWIR) regime for visualizing and tracking trace gas content of the outflow from BB events, explicitly addressing the need for spatially resolved measurements.

An initial set of flights was conducted in early September 2019 shortly after the NOAA/NASA Fire Influence on Regional to Global Environments and Air Quality (FIREX-AQ) intensive field campaign (Warneke et al., 2023). The 204 Cow Fire was one of those highlighted in Warneke et al. (2023) and was also amongst those investigated on this deployment, which were located in Oregon and Northern California. A second investigation was mounted more than a year later to study several wildfires in Central and Southern California. The fires sampled during both campaigns are listed in the accompanying table.

Name	URL	Date
204 Cow Fire	data.rgj.com/fires/incident/6526/204-cow-fire	2019-09-06
Lone Fire	en.wikipedia.org/wiki/Lone_Fire	2019-09-07
Walker Fire	en.wikipedia.org/wiki/Walker_Fire_(2019)	2019-09-07
Blue Ridge Fire	www.fire.ca.gov/incidents/2020/10/26/blue-ridge-fire	2020-10-27
Silverado Fire	en.wikipedia.org/wiki/Silverado_Fire	2020-10-27
Creek Fire	en.wikipedia.org/wiki/Creek_Fire_(2020)	2020-10-28

To our knowledge these are the first correlated, quantified measurements of wildfire co-emissions obtained with an airborne imaging spectrometer and demonstrate a means for acquiring data that can assist the elucidation of chemical-dynamic processes occurring in wildfire outflow plumes.

Methodology

The sensor used for the work reported here ("Mako") is a 3-axis stabilized cryogenically cooled high-throughput LWIR spectrometer coupled to a fast-readout focal plane array. This combination allows high sensitivity measurements to be made with short dwell times, so that whiskbroom scanning can be implemented to permit high areal acquisition rates (Buckland et al., 2017). Areal rates up 1430 km^2/h from a flight altitude of 12000 ft (3.6 km) above ground level (AGL) with 2-m ground sample distance (GSD) have been demonstrated. The spectroradiometric performance of Mako is given in the table below.

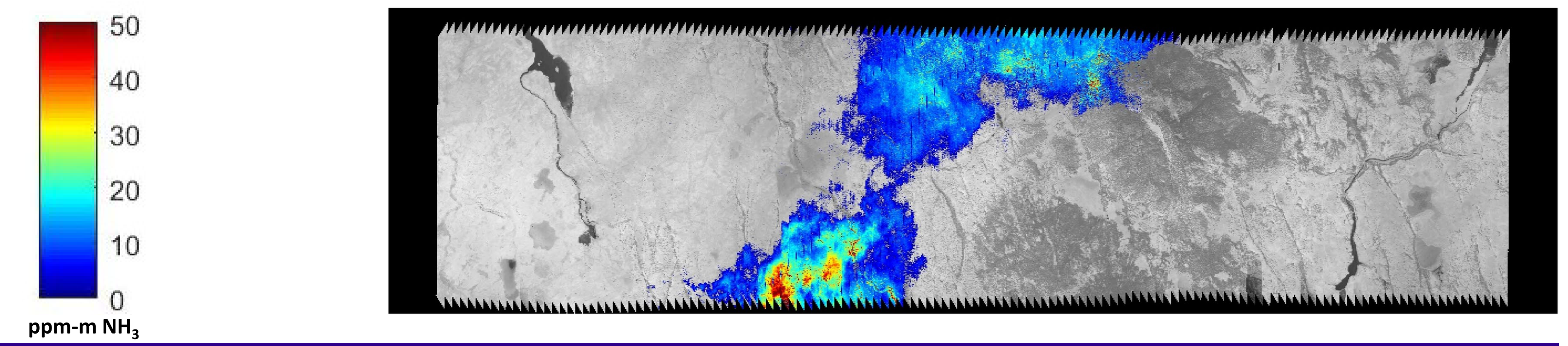
Parameter	Specification
Spectral coverage	7.57 – 13.16 µm
Spectral sampling and resolution (128 channels)	44 nm
Instantaneous field-of-view, IFOV	0.55 mrad
Along-track FOV (128 pixels per frame)	4°
Typical operational frame rate (4-frame coadding)	814 Hz
Cross-track pixels (user selectable)	400 – 3600
Cross-track field-of-regard, FOR (relative to nadir)	±56.4° (maximum)
Noise-equivalent spectral radiance, NESR (10 µm, 4 coadds)	<0.3 µW cm^{-2} sr^{-1} µm^{-1}
Noise-equivalent differential temperature, NEdT (10 µm, 300 K)	0.02 K

The data handling and processing procedures used to extract spectral information from the imagery and identify gases present in the scene have been described in detail by Buckland et al. (2017). Column content maps of BB trace gases were created using the Scene-based Algorithm for Gas Estimation (SAGE) tool.

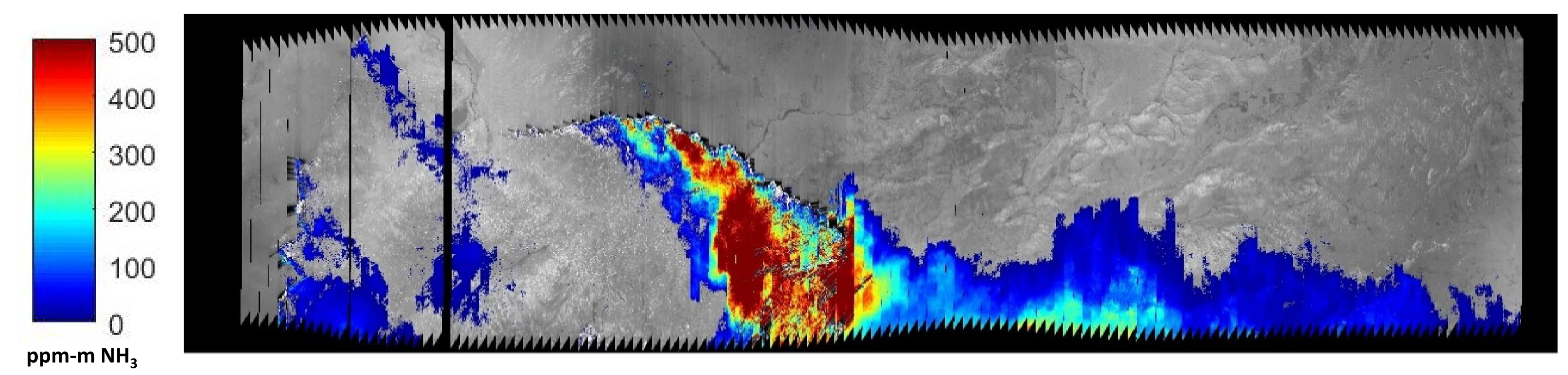
At the core of SAGE is a non-linear quantitative radiative transfer model that incorporates interactions between the trace gases under study, the scene underlying the BB plume, and the atmospheric column between the plume and the sensor. A portion of the scene substantially free of the trace gases under investigation is used to compute BB-gas-free scene eigenvectors, following which the entire scene may be queried for the target gas spectra.

Area Emissions of Ammonia

The sensor is especially sensitive to ammonia and this gas was observed in profusion from the wildfires investigated in this work. The figures below depict ammonia emissions from three of these events superimposed on gray-scale thermal radiance imagery. The swath widths (short dimension of image) are approximately 2.5 km.



Lone Fire, Modoc County, California; 7 Sep 2019.



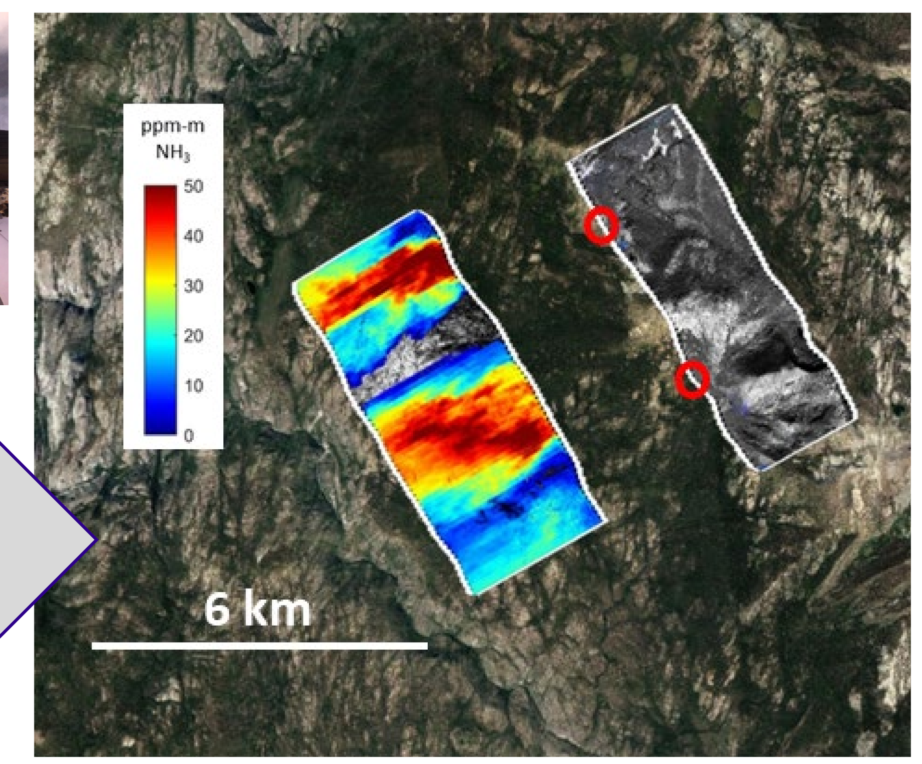
Walker Fire, Plumas County, California; 7 Sep 2019.

Walker Fire, Plumas County, California (7 Sep 2019), as seen from the air.

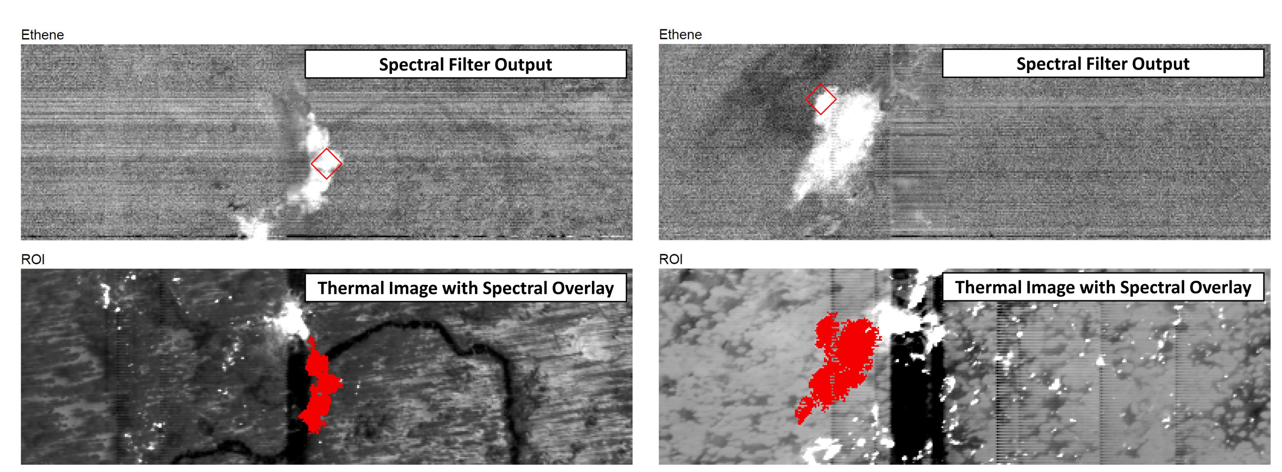
Creek Fire, Fresno County, California; 28 Oct 2020.

The Creek Fire was amongst the largest and most destructive in modern California history, consuming almost 380,000 acres (154,000 ha) of predominantly the Sierra National Forest.

The two red circles denote the locations of discrete fires whose ammonia emissions appear downwind in the image to the west.

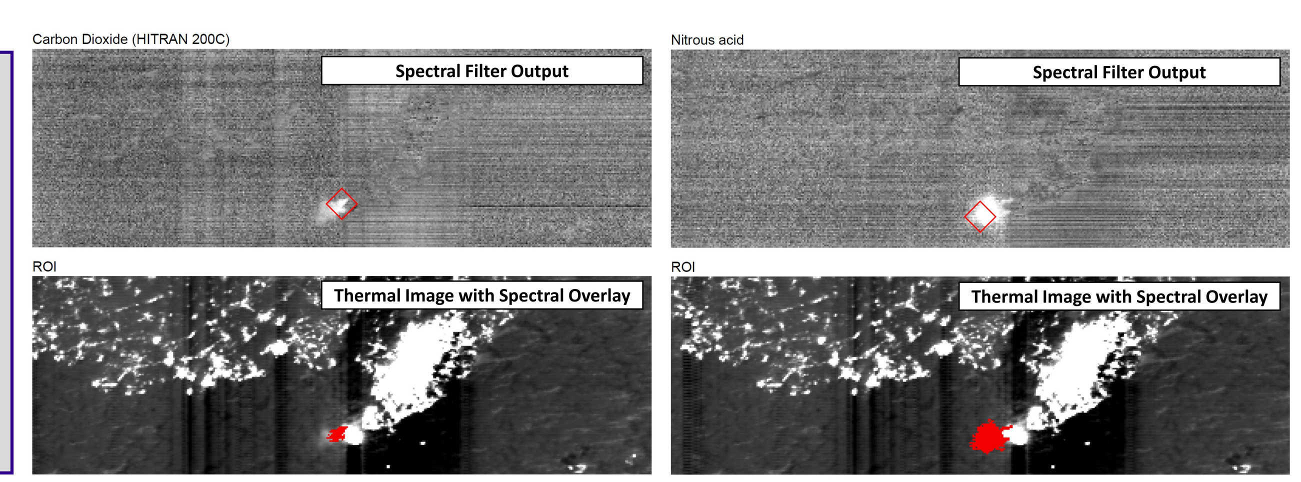


Creek Fire Emissions



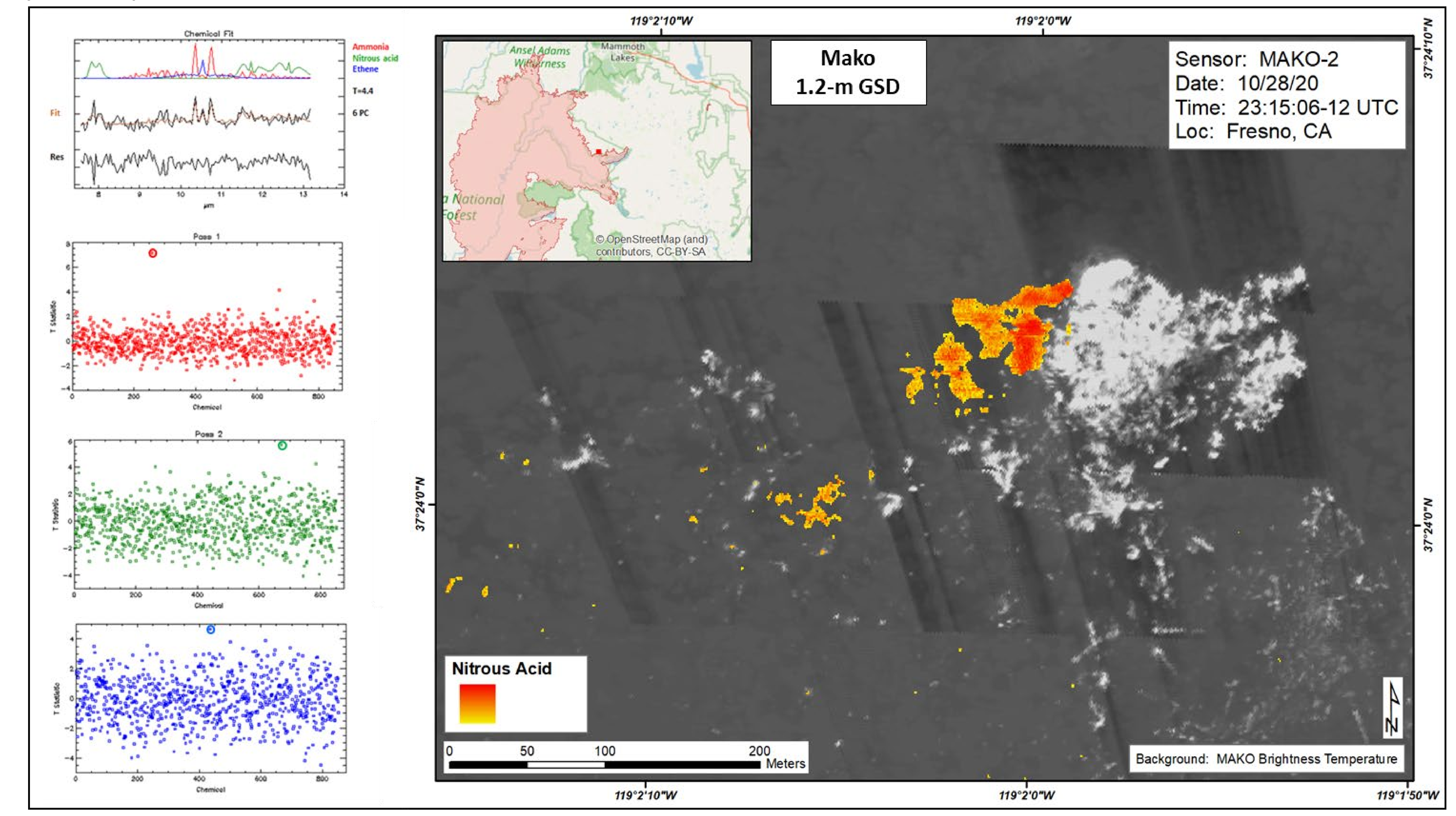
The sensor is also highly sensitive to ethene, which was also observed often in this BB investigation. The two plumes seen at left emanate from different fire fronts at the Creek Fire.

A number of binary and ternary plumes were observed during the course of this work. Both CO_2 and nitrous acid (HONO) were identified in the fire front emission shown at right.



Discrimination of Individual Co-emission Components

One instance in particular serves to illustrate the power of LWIR spectral imaging for determining the chemical content of gaseous BB emission plumes. The example depicted below shows a HONO detection image from the Creek Fire. Immediately to its left is shown the multi-component analysis of the plume along with a confidence metric (t-statistic), which is seen to contain ammonia and ethene in addition to HONO. This ability to unmix co-emitted gases has application to the improved elucidation of chemical-dynamic processes active in BB outflows.



Concluding Remarks

The specific ability of airborne LWIR spectral imaging for visualizing and tracking trace gas content of the outflow from BB events explicitly addresses the stated need for spatially resolved measurements (Palm et al., 2021) and should be considered for inclusion in future wildfire investigations.

The principal limitation faced by the technique at this time is the quantification uncertainty introduced by imperfect knowledge of the prevailing air temperature, which is especially difficult to ascertain in BB environments. Guo et al. (2021) have pointed out the sensitivity of retrieval accuracy to the atmospheric boundary layer temperature knowledge.

To address this issue, it is suggested that contemporaneous measurements by a co-manifested LWIR spectral imager, FTIR sounder, and an aerosol lidar to constrain the plume boundaries (Tratt et al., 2016) would enable the recovery of absolute gas mixing ratios with greater accuracy. Kuai et al. (2019) have additionally suggested that an accompanying multiangle polarimeter would assist in the characterization of gas-to-particle conversion processes for gases such as ammonia that contribute to aerosol generation by BB. Such a sensor suite deployed for future BB campaigns analogous to FIREX-AQ and FireSense would yield a comprehensive data set of considerable value to fire science objectives.

References

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