RETRIEVAL OF TEMPERATURE AND SPECIES DISTRIBUTIONS FROM MULTISPECTRAL IMAGE DATA OF SURFACE FLAME SPREAD IN MICROGRAVITY

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INTRODUCTION

Weight, size, and power constraints severely limit the ability of researchers to fully characterize temperature and species distributions in microgravity combustion experiments. A powerful diagnostic technique, infrared imaging spectrometry, has the potential to address the need for temperature and species distribution measurements in microgravity experiments. An infrared spectrum imaged along a line-of-sight contains information on the temperature and species distribution in the imaged path. With multiple lines-of-sight and approximate knowledge of the geometry of the combustion flowfield, a three-dimensional distribution of temperature and species can be obtained from one hyperspectral image of a flame. While infrared imaging spectrometers exist for collecting hyperspectral imagery, the remaining challenge is retrieving the temperature and species information from this data.

An initial version of an infrared analysis software package, called CAMEO (Combustion Analysis Model et Optimizer), has been developed for retrieving temperature and species distributions from hyperspectral imaging data of combustion flowfields. CAMEO has been applied to the analysis of multispectral imaging data of flame spread over a PMMA surface in microgravity that was acquired in the DARTFire program. In the next section of this paper, a description of CAMEO and its operation is presented, followed by the results of the analysis of microgravity flame spread data.

CAMEO ANALYSIS METHODOLOGY

CAMEO uses a nonlinear model matching approach to analyze imaging spectrometer data. This approach, as shown in Figure 1, consists of two main parts. The first part is a numerical model of the measured data. This model must treat both the physical process that produces the infrared signal, such as the PMMA surface combustion modeled in this work, and the measurement process that produces the hyperspectral or multispectral image data. In general, the numerical model requires inputs to describe both the physical process and the measurement process. The second part of the nonlinear model matching approach is an optimizer that iteratively modifies the inputs to the model to produce a predicted data set that matches the measured data.

The analysis procedure, as indicated in Figure 1, starts with the initial input parameter estimates being read by the optimizer and then passed to the model to generate a set of predicted measurements, i.e., a predicted hyperspectral or multispectral image data set. The optimizer then compares the predicted data set with the measured data set, calculates an objective function value that represents the overall difference between the measured and predicted data sets, and then generates a new set of parameter estimates that are passed to the model. The model generates an updated predicted data set from these new parameters and passes the updated set to the optimizer for evaluation. This process is repeated until the optimizer determines that it has found the set of input parameter estimates that provides the best match between the predicted and measured data sets.

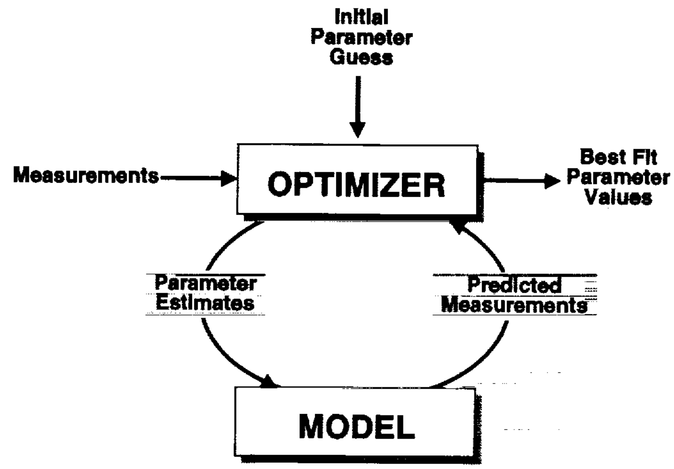


Figure 1 Nonlinear Model Matching Methodology

The numerical model component of CAMEO consists of subroutines for two separate models, one to model the physical process producing the infrared signal, and a second to model the generation and measurement of the infrared signal. At the heart of this second model is a three-dimensional radiation transport code, RAD3D, developed by Aerodyne. RAD3D computes the spatially and spectrally resolved infrared signal from a three-dimensional distribution of temperature and species. RAD3D uses band models to calculate the infrared emission and absorption by the infrared-active species in the combustion flowfield. Additional routines then convert the hyperspectral image computed by RAD3D to a form that allows a comparison with the measured data.

In the present version of CAMEO, the model of the physical process that produces the infrared signal must be supplied by the user for each class of combustion process, or other physical process, to be analyzed. This model must generate a flowfield description, i.e., distributions of temperature and species concentrations, as a function of model input parameters. The complexity of this model can range from empirical to detailed. An empirical model, for example, may use a prescribed shape of the flame front and determine the distribution of species and temperatures based on functional forms for temperature and species in various regions of the combustion flowfield. The inputs to this model are typically the parameters used in the functional form descriptions of the species and temperature distributions. This type of model was used in analyzing the PMMA flame spread data. A detailed model may use a "first principles" approach, with inputs perhaps being turbulence intensity, thermal and mass diffusivities, and characteristic lengths and velocities.

The optimizer used in CAMEO is a general constrained optimization package, NPSOL, using a sequential nonlinear programming algorithm[1]. In an initial study of optimizers, NPSOL was found to use the fewest number of function evaluations (iterations) to achieve a good match between measured data and predictions[2]. The sum of squared residuals was used as the objective function that was minimized by NPSOL to obtain the best match between data and prediction. While use of this normal Least Squares criterion is most common, NPSOL can also use objective functions based on Bayesian or Maximum Likelihood approaches to uncertainty in the measured data.

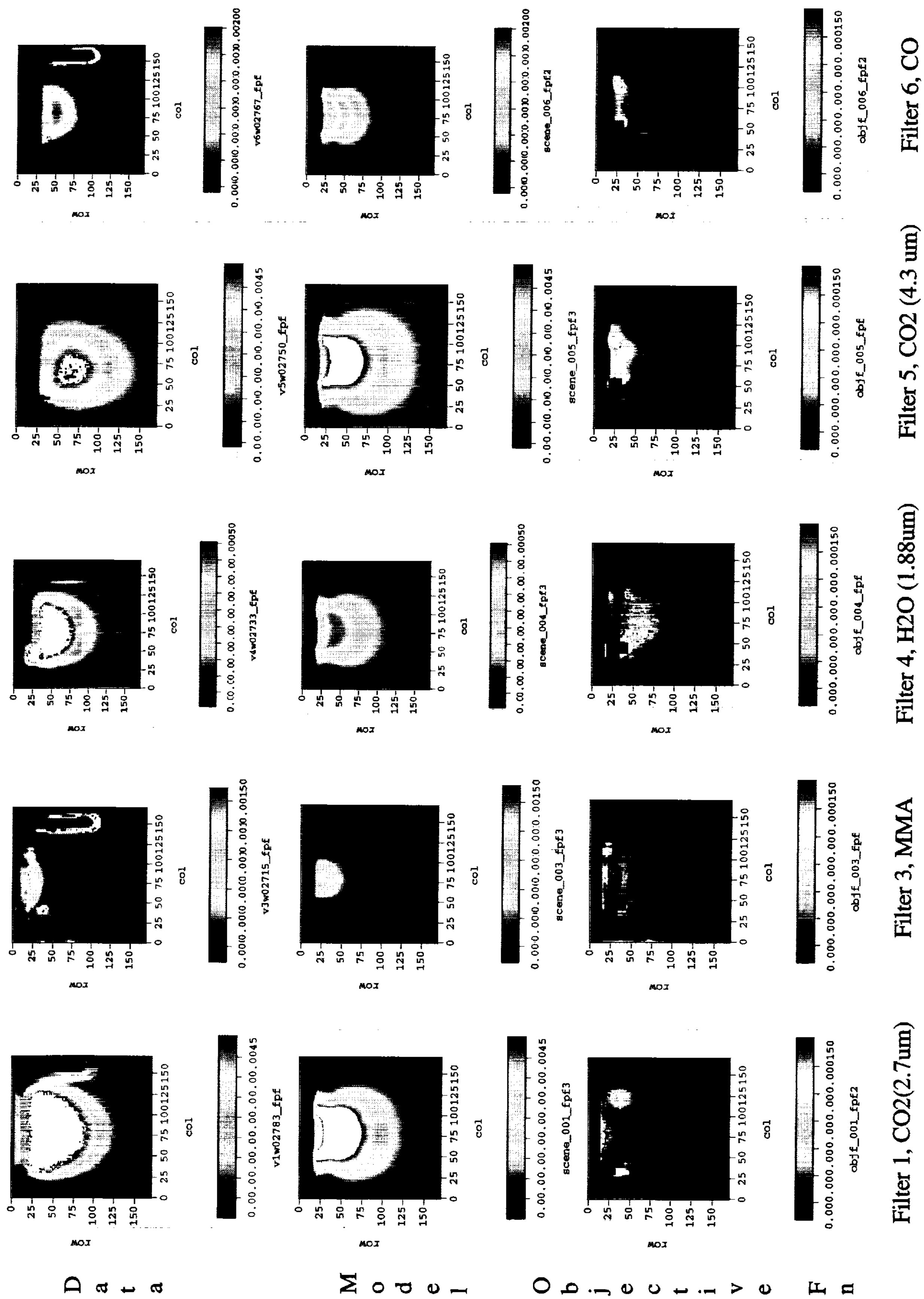
CAMEO ANALYSIS OF MICROGRAVITY FLAME SPREAD DATA

While CAMEO has been designed for the general application of analyzing hyperspectral image data, it also can analyze multispectral imagery, such as collected in the DARTFire program[3]. The DARTFire data consist of a set of six images, each for a different bandpass filter. The filters covered the 1.88 μm H_2O band, CO_2 bands at 2.7 and 4.3 μm, MMA band at 3.4 μm, and CO band at 4.8 μm. For this data analysis, the hyperspectral image computed by RAD3D is integrated over modified filter transmission curves to obtain six images for comparison with the data. The modified filter curves account for the variation in detector response over the filter bandpass regions. For analysis with CAMEO, the raw DARTFire images containing eight-bit detector intensity information were converted to images containing radiance values. This conversion also introduced "flag" values for locations where the measured radiance was below the detector sensitivity limit. These regions are used in calculating the objective function if the predicted radiances are greater than this low limit value. As mentioned above, an empirical approach was used to model the PMMA flame spread combustion flowfield. A flame front location is defined by the user by specifying a number of points to which a spline curve is fit. Profiles for temperature and species are defined for two regions: the fuel rich region between the flame front and pyrolizing PMMA surface, and the fuel lean region outside the flame front.

Analysis of the multispectral flame spread imagery has posed a number of challenges, primarily due to the three-dimensional character of the actual combustion flowfield, the relatively simple nature of the empirical model of the flowfield, and the low spectral resolution of the data. Initial attempts to analyze the data using a two-dimensional empirical model failed to closely reproduce the radiance images. After the empirical model was extended to account for flame height variation in the transverse direction, an improved agreement with the radiance images was obtained. The figure plate on the following page shows the data images for five bands in the top row, the "optimized solution" model images in the middle row, and the objective function (proportional to the square of the residual) on the bottom row. The band for each column is given at the bottom of the plate. Differences in the radiance spatial distributions between the data and model clearly exist, though considering that a single distribution of temperature and species concentrations produces the different distributions for the five filter bands shown in the plate, the agreement is reasonable. The agreement between the data and model on the peak radiances in each filter band is generally quite good. The peak radiances agree exactly for Filter 3 (MMA), within 5% for Filter 5 (CO_2-4.3 μm), 12% for Filter 1 (CO_2-2.7 μm), and 25% for Filter 6 (CO). The only substantial mismatch is Filter 4 where the model intensity is low by almost a factor of two. This mismatch could possibly be caused by inaccuracies in the band model for H_2O, since a detailed model for this band was not available.

The objective function images in the figure plate show where the major regions of difference between the data and model exist for each band. With the exception of the H_2O band, the regions of greatest difference are near the PMMA surface at the leading or trailing edge of the flame. Thus, the inability of the simple empirical model to represent the details of the flowfield in this region accounts for the largest discrepancies. In the center region near the flame zone, the agreement is quite good, as indicated by the agreement of the peak radiances cited above. While improvements in CAMEO to reduce run time and improve its geometric flexibility are desirable, CAMEO has produced encouraging results on this difficult analysis problem.

1. P.E. Gill, et al., NPSOL (Version 4.0): A Fortran Package for Nonlinear Programming, Systems Optimization Laboratory Report SOL 86-2, Dept. Operations Research, Stanford Univ., 1986.
2. E.R. Niple, K.D. Annen, and J.C. Wormhoudt, "Analysis Tools for Spectrally-Resolved and Broadband IR Imaging Data," Final Report, NASA LeRC Contract No NAS3-27267, July 1995.
3. S.L. Olson, et al., "Diffusive and Radiative Transport in Fires Experiment: DARTFire," Fourth International Microgravity Combustion Workshop, NASA CP-10194, p.393, May 1997.


Data
Model
Objective Fn
Filter 1, CO2(2.7um)
Filter 3, MMA
Filter 4, H2O (1.88um)
Filter 5, CO2 (4.3 um)
Filter 6, CO
v1w02783_fpf
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objf_001_fpf2
v3w02715_fpf
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row
col