Estimating Fire Properties by Remote Sensing[1].

Philip J. Riggan
USDA Forest Service
Pacific Southwest Research Station
4955 Canyon Crest Drive
Riverside, CA 92507
909 680 1534
PJRiggan@IBM.net

James W. Hoffman
Space Instruments, Inc.
4403 Manchester Avenue, Suite 203
Encinitas, CA 92024
760 944 7001
JHoffSI@AOL.com

James A. Brass
NASA Ames Research Center
Moffett Federal Airfield, CA 94035
650 604 5232
JBrass@mail.arc.nasa.gov

Abstract---Contemporary knowledge of the role of fire in the global environment is limited by inadequate measurements of the extent and impact of individual fires. Observations by operational polar-orbiting and geostationary satellites provide an indication of fire occurrence but are ill-suited for estimating the temperature, area, or radiant emissions of active wildland and agricultural fires. Simulations here of synthetic remote sensing pixels comprised of observed high resolution fire data together with ash or vegetation background demonstrate that fire properties including flame temperature, fractional area, and radiant-energy flux can best be estimated from concurrent radiance measurements at wavelengths near 1.6, 3.9, and 12 µm, Successful observations at night may be made at scales to at least I km for the cluster of fire data simulated here. During the daytime, uncertainty in the composition of the background and its reflection of solar radiation would limit successful observations to a scale of approximately 100 m or less. Measurements at three wavelengths in the long-wave infrared would be unaffected by reflected solar radiation and could be applied to separate flame properties in a binary system of flame and background. However, likely variation in the composition of the background and its temperature limit the approach to measurements that are of high resolution in relation to the scale of the flaming front. Alternative approaches using radiances at wavelengths near 4 and 12 µm alone must fail absent a correction for the background, yet the correction is made imprecise by uncertainty in composition of the background where it comprises more than one-third of a pixel.

TABLE OF CONTENTS

INTRODUCTION

More than 30,000 fire observations were recorded over central Brazil during August 1999 by Advanced Very High Resolution Radiometers operating aboard polarorbiting satellites of the U.S. National Oceanic and Atmospheric Administration. At the same time an extensive smoke pall created a serious health hazard and hindered commercial aviation across large portions of the Brazilian states of Mato Grosso and Mato Grosso do Sul. Clearly fire was an important part of the Brazilian environment, but limitations in satellite and airborne remote sensing prevented a clear picture of what was burning, what resources were threatened, or the magnitude of the potentially global environmental impacts. Indeed, these fires and others like them throughout the tropics may constitute an important source of greenhouse gases that may be contributing to climate change.

The government of Brazil, through the Brazilian Institute of the Environment and Renewable Natural Resources (IBAMA), is developing a national means to monitor and manage fire impacts. But the sheer number of fire starts is overwhelming, and the many recorded mask the few that are most threatening to resources or contribute the most to air pollution and health concerns. A system for prioritizing fires based on measured impacts and threatened resources would be most welcome. Furthermore, a continental-scale assessment of impacts is needed to support development of national policies on fire management. Needed at tactical, strategic, and policy levels is fundamental information on fire extent, intensity, rate of progress, fuel consumption, and gas and particulate emissions.

Advances in airborne thermal-infrared imaging systems over the last decade have produced the first quantitative, synoptic measurements of the thermal properties of wildland fires [1]. Furthermore, new imagers based on uncooled, thermal-infrared detectors are being developed as a low-cost means of monitoring fire size and intensity at a local or regional level [2]. What is needed to address fire measurements at a continental or global scale is a system that can similarly measure fire properties from a high-altitude or space-based platform. A design for such a system must take into account issues of scale and resolution in order to make meaningful environmental measurements.

In this paper, we use fire measurements made by the NASA/Forest Service airborne Extended Dynamic Range Imaging Spectrometer, which was designed specifically to measure the high radiances associated with wildland fires, to consider how changes in measurement scale and channel wavelength would affect estimates of fire temperature, size, and radiant intensity. These properties, in turn, are key to the fundamental information requirements of fire management.

ESTIMATING FIRE PROPERTIES

Wildland fires present a complex remote sensing target comprised of a flaming front, ash, residual flaming combustion and smoldering of larger biomass elements, and unburned vegetation. Flames within the flaming front are highly dynamic and turbulent in comparison with the rate of spread of that front.

To estimate fire properties by remote sensing we assume that the radiant emissions of flames are dominated by the radiation from glowing soot particles that behave as graybody radiators with high emissivity. Individual flames may be optically thin so that upwelling radiation encompasses that from hot soil beneath the flames as well as from the entrained soot particles. For large flames or those of high soot-particle volume, upwelling radiation may reflect the temperature of upper flames alone. However, flaming zone turbulence may so great as to dictate that high-temperature flames occupy only a fraction of a remote sensing pixel, even for pixels falling well within a flaming front, and a parameter representing the product of emissivity and fire fractional area must be estimated.

ESTIMATES FROM TWO CHANNELS

The temperature, *T*, of a gray-body radiator and the product of its emissivity, ε, and fractional area, A_f within a pixel can be independently estimated from emitted energy measured at two wavelengths, λ_1 and λ_2 [1,3]. Planck functions for the target radiances, $B\lambda_2$ and $B\lambda_1$, may be solved simultaneously yielding the relations

$$\beta\lambda_2/\beta\lambda_1 = \frac{\lambda_1^5(\exp(hc/k\lambda_1 T)-1)}{\lambda_2^5(\exp(hc/k\lambda_2 T)-1)} \quad (1)$$

and

$$\varepsilon A_f = B\lambda_i\lambda_i^5(\exp(hc/k\lambda_i T)-1)/(2\mathrm{x}10^{-6}hc^2) \quad (2)$$

where h is the Planck constant, $6.63\mathrm{x}10^{-34}$ (J s); c is the speed of light, $3.00\mathrm{x}10^8$ (m/s); k is the Boltzmann constant, 1.38x10-23 (J/K); T is specified in Kelvin; , λ is in meters, and B_λ has units of J m^{-2} s^{-1} sr-1 μm^{-1}. Equation (1) may be solved iteratively to yield T, and the product εA_f can be computed from either wavelength via Equation (2).

We have applied this approach to estimate temperatures and the combined emissivity-fractional area parameter, εA_f for a large Cerrado or tropical savanna fire 50 km north of Brasilia in the Federal District of Brazil. (Figure 1). The fire was observed late in the afternoon on September 15, 1992, toward the end of the dry season. The fire burned freely in mountainous terrain with mixed grass and woodland plant communities. It attained a complex structure with narrow, hot flaming fronts in grasses and large areas of residual combustion in heavier fuels.

Remote sensing observations were made in channels with wavelengths centered at 1.63, 3.9, and 11.9 μm and with resolution of 3.1 m giving a nominal pixel size of 9.6 m^2. Fire temperatures were estimated from this high resolution data using the two short-wave infrared channels at 1.63 and 3.9 μm.

This fire had a complex thermal structure with 95 percent of the radiant-energy flux density obtained from pixels with temperatures ranging from 850 to 1400 K (Figure 2). High temperature pixels were associated with generally low values of the emissivity-fractional area parameter, even at high (3.1 m) resolution. This suggests to us that the flames were either optically thin or spatially heterogeneous at scales from one to several meters.

To examine the effect of observation scale we simulated the radiant properties of a limited area of complex fire line viewed in isolation with differing amounts of background at temperatures of either 303 K, representing savanna vegetation, or 343 K, representing black ash in full sun. Synthetic pixels were constructed from the high resolution hot pixels observed within a 50 m by 50 m area at the southwest corner of the Serra do Maranhao fire.

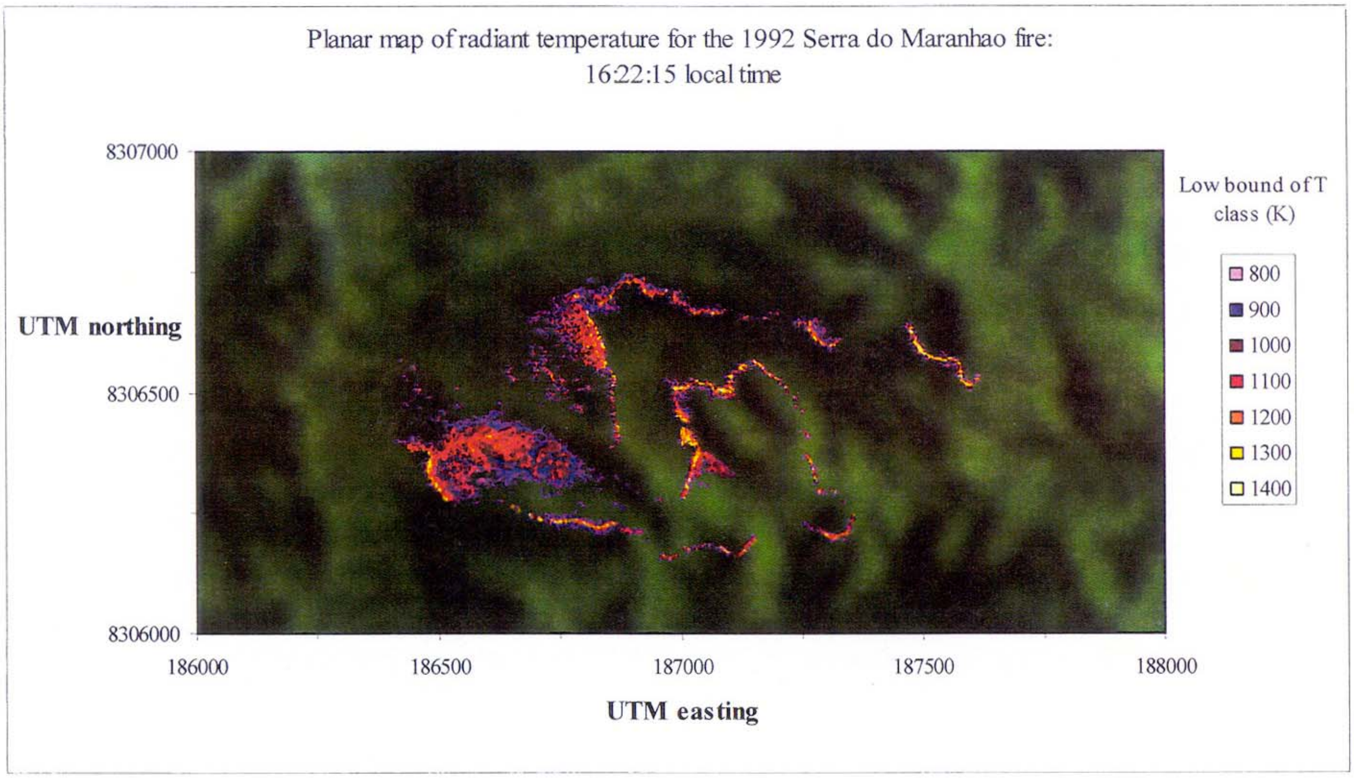


Figure 1. Temperature map for a freely burning wildland fire in tropical savanna vegetation in the Serra do Maranhao, Federal District, Brazil. Fire pixels are color coded by temperature class and shown on a background derived from a prefire Landsat Thematic Mapper image. Light green areas are grassland; darker areas are heavier woody vegetation. Universal Transverse Mercator coordinates are shown. The fire extends approximately 1.2 km from west to east.

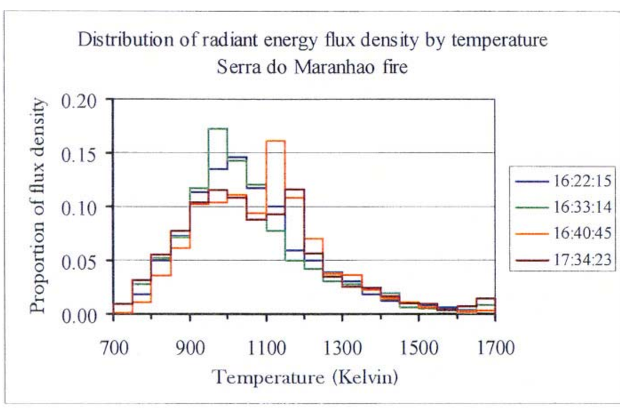


Figure 2. Distribution of radiant-energy flux density by temperature for four observations of a savanna fire in the Serra do Maranhao of the Federal District of Brazil. Ninety-five percent of the energy flux occurred over temperatures between 850 and 1400 K.

Spatial compression of this hot-pixel data by excluding the low temperature background would yield a single pixel with a linear dimension of 41.8 m. To simplify calculations we made the assumption that pixels are square and non-overlapping.

Comparisons were made between the high-resolution blackbody radiance distribution with wavelength, as summed across all elements of the synthetic pixel, and the distribution derived from the bulk temperature and fractional area of that low-resolution pixel. The latter bulk parameters were derived from Equations 1 and 2 using the sum of radiances across sub-pixel elements at each of two wavelengths. We also estimated the high resolution radiance from flames alone. Emissivity of vegetation, ash, and soot particles are expected to be 0.9 or greater [c.f. 4] so the assumption of a blackbody for our purposes was reasonable.

The bulk temperature and fractional area estimated at wavelengths of 1.63 and 3.9 μm for the low resolution pixel described well the overall radiance distribution for the *compressed* hot-element data, despite the large range of incorporated temperatures and fractional areas. The wavelength-integrated radiance of 1155 J m^{-2} sr^{-1} s^{-1}, derived from an estimated bulk temperature of 1107 K and fractional area of 0.044, was nearly equivalent to the integrated high-resolution radiance of 1158 J m^{-2} sr^{-1} s^{-1} obtained by summing values from the individual high temperature elements. A bulk temperature of 1057 K and fractional area of 0.052, as derived from radiances at wavelengths of 3.9 and 11.9 μm gave a less successful estimate of 1126 J m^{-2} sr^{-1} s^{-1} for the wavelength integrated radiance.

As the synthetic pixel was enlarged, the relatively low temperature of the included background quickly elevated the radiance at wavelengths longer than 6 µm, but had little effect on the radiance in the short-wave infrared (Figure 3). Thus, use of the radiances at 1.63 and 3.9 µm to estimate bulk temperature and fractional area produced a good description of the high temperature elements within synthetic pixels with a dimension less than approximately 100 m (Figures 4 & 5).

The relatively strong contribution of the background to the long-wave infrared radiance dictates that any attempt to directly estimate the hot element properties from those of a low-resolution pixel using two wavelengths including the long-wave infrared must largely fail without some correction for the background. For a 75-m synthetic pixel, use of the 3.9 and 11.9 µm wavelengths produced an estimated bulk temperature, 708 K, that described neither the hot elements at 1107 K nor the background at 303 K (Figure 6).

The required background correction for daytime remote sensing using this scheme is at best problematical for the simple reason that fires generate an ash layer that under solar heating may be 40 K warmer than unburned ground, and there is no way to know a priori the proportion of these differing targets within a low-resolution pixel. Since the background may be all ash or all unburned vegetation, and the magnitude of this uncertainty amounts to half of the simulated fire signal in a 125-m pixel and

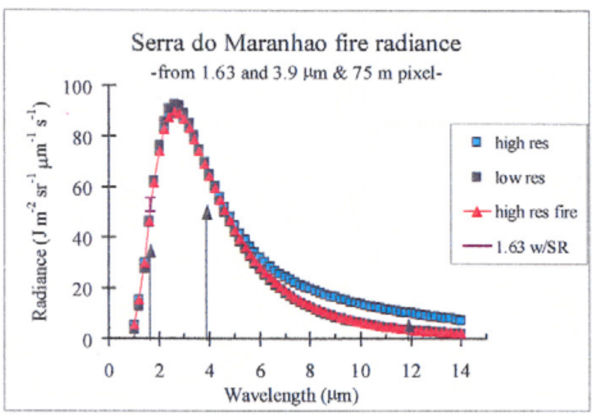


Figure 3. Simulated blackbody radiance distributions for a low-resolution synthetic pixel of 75 m linear dimension. Sub-pixel elements include an assumed 303 K background covering 69 percent of the pixel and all hot targets from within a 50- by 50-m area at the SW corner of the Serra do Maranhao Fire as shown in Figure 1. Shown are the summed radiances as viewed at high resolution, for the entire pixel ("high res") and the fire alone ("high res fire"), and the low-resolution radiance distribution ("low res") as computed from bulk temperature, fractional area, and the summed sub-pixel radiances at 1.63 and 3.9 µm.

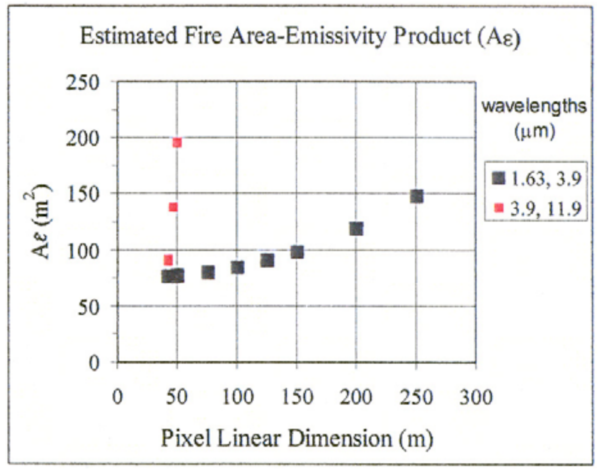


Figure 4. Comparison of the estimated hot target area (the product of fire fractional area and emissivity with pixel area) as a function of synthetic pixel size as determined using wavelengths either of 1.63 and 3.9 µm or 3.9 and 11.9 µm. The former pair produces errors of less than 11 percent at pixel sizes less than 100 m; the latter produces substantial errors at even the smallest pixel size due to a lack of fit to the Planck function by the composite high-temperature data as viewed at those wavelengths.

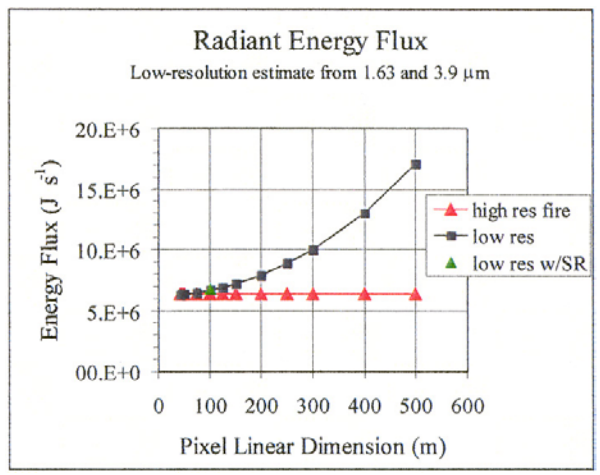


Figure 5. Comparison of estimates of the low-resolution radiant energy flux, determined at 1.63 and 3.9 µm, with the energy flux from included high-temperature elements. Background temperature was assumed to be 343 K. Pixels with a size of 125 m, for which the background comprises 0.9 of the pixel, introduce less than a 10 percent error in this measure of total fire intensity. Uncertainty in the composition of the background and, therefore, the reflected solar radiation at 1.63 µm, produces only a small error in estimated energy flux for 100-m pixels ("low res w/SR").

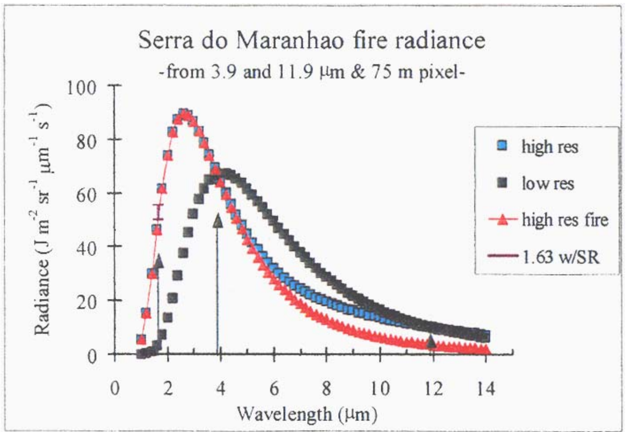


Figure 6. Simulated black-body radiance distribution as in Figure 3, but with the low-resolution radiance distribution computed from the summed sub-pixel radiances at 3.9 and 11.9 µm. Use of the long-wave infrared signal produces a substantial error in pixels at any resolution less than that of the high-temperature elements.

over twice the fire signal at 250 m resolution, this approach, too, fails when pixel sizes greater than approximately 50 m are used to view the sample fire data. At that scale the uncertainty is only 3 percent of the fire signal.

Daytime remote sensing with the short-wave infrared may require a background correction for reflected solar radiation, primarily at 1.63 µm, but this is less critical than the correction for the long-wave infrared. The uncertainty in the composition of the background, between extremes either of all ash or all vegetation, produces only an additional 2 percent error in the estimated radiant energy flux with a 100-m synthetic pixel (Figure 5).

So far we have analyzed the effect of embedding a moderate-size cluster of fire pixels within a series of synthetic pixels of increasing size. With a larger fire, increasing the area viewed in a single pixel must increase not only the background but also the amount of included fire. We simulated this effect with data from the Serra do Maranhao fire by selecting all high-temperature pixels within areas of 100 by 100 m, 250 by 250 m, and 1 km by 1 km beginning at the southwest portion of the fire. High-resolution, high-temperature pixels occupied 57.7 percent of the 100- by 100-m selection area, 42 percent of the 250- by 250-m area, and 6.5 percent of the 1-km^2 area. The result, considering emitted energy alone and a 303 K background, was that radiances at wavelengths of 1.63 and 3.9 µm described well the radiance distribution and bulk temperature (within 1 K) of the embedded high temperature targets for both 100-m and 250-m pixels. The low-resolution estimate was within 9 K of the bulk flame temperature and radiant energy flux was within 3% of the true value for the 1-km^2 case. Use of 3.9 and 11.9 µm wavelengths resulted in significant lack of fit to the high-temperature radiance distribution for 100-m and larger pixels. In this case, the bulk temperature of the hot elements was underestimated by 190 K for 100-m pixels, 250 K for 250-m pixels, and 585 K for 1-km pixels with a background temperature of 303 K.

MULTI-SPECTRAL FIRE IMAGING

The foregoing analysis has been based on a selection of fire data as measured at high (9.6-m^2) resolution and wavelengths of 1.63 and 3.9 µm. With generally low values of the apparent fractional area, it appears that there may be a substantial contribution to the 3.9 µm signal from hot background within the pixel. If so, then the flame temperatures we estimated may be low.

In order to examine this possibility, we devised an algorithm to estimate the fractional areas and temperatures of flame and background within a high emperature pixel based on radiances measured at three wavelengths and a model where the fractional areas of the two components sum to one. The three-wavelength algorithm proceeds as follows:

1. Flame temperature and fractional area are estimated using Equations 1 and 2 and observed radiances at 1.63 and 3.9 µm.
2. The flame radiance at 11.9 µm is estimated from the resultant values.
3. The radiance of the background at 11.9-µm is estimated as the difference between the observed value for the pixel and that of the flames. Background temperature is computed from this radiance assuming the background acts as a blackbody.
4. Background radiances at 1.65 and 3.9 µm are computed from the background temperature and fractional area, and flame radiances at these wavelengths are estimated from the difference between observed values and those of the background.
5. Steps 1 to 5 are iterated using successive estimates of flame radiance until a stable estimate of flame temperature is achieved.

We applied the three-wavelength algorithm to a selection of line-fire data collected by the Extended Dynamic Range Imaging Spectrometer in Central Brazil. In this case the 11.9-µm channel had a relatively low signal-to-noise ratio, so we estimated likely values for individual high-resolution pixels based on a regression of radiance at 11.9 µm to that at 3.9 µm. The result was that estimated flame temperatures rose by an average of approximately 60 K over that estimated by two channels alone, and the average background temperature within high temperature pixels was estimated to be 440 K.

This three-wavelength algorithm appears to be useful for separating radiance contributions from flames and hot background across a wide range of temperatures and combinations of wavelengths. As an example, we constructed synthetic radiance data (Figure 7) based on a pixel with flame temperature and fractional area equivalent to those of the spatially compressed hot pixel data from the 50- by 50-m area at the southwest of the Serra do Maranhao fire (as simulated in Figure 3) together with a variety of background temperatures.

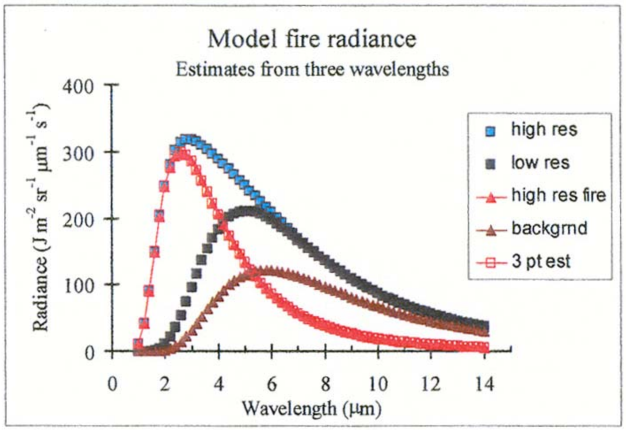


Figure 7. Model fire radiance and estimation of flame temperature, background temperature, and fractional areas using three long-wave infrared radiances. Shown are the radiance distributions for flames at 1107.4 K with fractional area of 0.0439 (the average values for a portion of the Serra do Maranhao fire), a 500 K background occupying the remaining fraction of the pixel, the sum of these two components, a low-resolution estimate derived from the combined radiances at 8 and 10 μm, and a three wavelength estimate of flame radiance derived from the combined-element radiances alone at 8, 10, and 12 μm ("3 pt est"). The three-wavelength estimate, which successfully separated the radiance distributions of the flames and background, is coincident with that of the modeled fire.

The algorithm successfully estimated the temperatures and fractional areas with any of three combinations of selected wavelengths: 1.63, 3.9, and 11.9 μm; 3.9, 8, and 12 [Lm; and 8, 10, and 12 μm. Convergence to a solution was notably longer in the latter category, requiring 1050 iterations to attain the specified flame temperature. Even so, estimated temperatures were within 0.1 K of that specified in the simulation regardless of the background temperature chosen. Thus, any high-resolution measurements at three wavelengths could be usefully applied to separate the temperatures and fractional areas of sub-pixel high-temperature and background elements in a binary system.

The solution using three longwave-infrared wavelengths, however, is unforgiving to a violation of the assumption of a uniform background. Enlarging the viewing pixel to include equal areas of background at 340 K and at 400 K produced an error of 148 K in the estimated flame temperature. Such a simulation using wavelengths of 1.63, 3.9, and 11.9 μm produced an error of only 3 K in estimated flame temperature. For a 1-km pixel, this selection of wavelengths produced an error of 5.4 K in temperature and 4-percent error in fractional area. Thus, the use of 8-, 10-, and 12-μm wavelengths has utility for separating flame and hot background components within pixels where the background is uniform, such as with high resolution within a flaming front. Measurements at wavelengths of 1.63, 3.9, and 11.9 μm can separate flame properties from that of a non-uniform background including large amounts of unburned ground at pixel sizes to 1 km.

APPLICATIONS FOR FIRE MONITORING

The foregoing analysis has shown that fire properties including flame temperature, fractional area, and radiant energy flux can best be estimated from concurrent radiance measurements at wavelengths near 1.6, 3.9, and 12 μm. At night, with no contribution of reflected solar radiation in the short-wave infrared, the observations may be made at scales to at least 1 km for the cluster of fire data simulated here. During the daytime, uncertainty in the composition of the background and its reflection of solar radiation would limit successful observations to a scale of approximately 100 m. Measurements near wavelengths of 1.6 and 3.9 μm alone could be made at a scale of 100 m, but the resolved flame temperatures may constitute an underestimate of approximately 60 K.

Measurements at three wavelengths in the long-wave infrared would be unaffected by reflected solar radiation and could be applied to separate flame properties in a truly binary system of flame and background. However, likely variations in the composition of the background and its temperature, especially between the immediate vicinity of flames and areas beyond their influence, would limit the approach to high resolution in relation to the scale of the flaming front.

A candidate system for this high-resolution application is the FireMapper, a multi-spectral, thermal-infrared imaging radiometer now under development as a research joint venture by Space Instruments, Inc., and the USDA Forest Service. The FireMapper employs an uncooled, micro-bolometer detector array manufactured by Lockheed Martin Imaging Systems [5] in a scientific instrument with automated radiometric calibration and real-time image control and display. FireMapper uses technology that has been demonstrated to have both high sensitivity and sufficient dynamic range to produce quantitative, unsaturated fire measurements [2]. FireMapper could also usefully contribute to a lower resolution, mufti-spectral system employing the threechannel approach with both shortwave and long-wave infrared wavelengths.

Estimates of active-fire properties obtained using existing low-resolution, two-channel sensors, such as those available on the NOAA polar orbiting and geostationary environmental satellites, are necessarily confounded with the background because of uncertainty in its composition, and not very meaningful beyond determination of a fire's presence. This information can be useful in showing regions in which fires are absent or numerous, and in providing a qualitative understanding of diurnal and seasonal patterns of occurrence. It should be used with great caution, however, as an indication of regional or global fire impact.

Radiance measurements at a single wavelength, such as near 3.9 µm, do not provide sufficient information to estimate both fire fractional area and temperature without assuming a value for one property or the other. Thus, they do not constitute a measurement of the desired fire properties and only a very poor indication of overall fire radiance.

We conclude that existing satellite-based systems are not now adequate for the task of providing the information needs for tropical fire management. A new approach is needed that employs unsaturated measurements at moderately high (100 m) resolution and wavelengths near 1.6, 3.9, and 12 µm in a satellite-based system with wide area coverage. As an alternative, multispectral thermal-infrared imaging radiometery now under development could be employed at high resolution from moderate- to high-altitude airborne platforms to provide the needed fire monitoring.

REFERENCES

[1] P. J. Riggan, J. A. Brass, and R. N. Lockwood. "Assessing Fire Emissions from Tropical Savanna and Forests of Central Brazil," *Photogrammetric Engineering and Remote Sensing* **59**(6):1009-1015, 1993

[2] P. J. Riggan and J. W. Hofnan.. "Field Applications of a Multi-spectral, Thermal Imaging Radiometer," Proceedings of the IEEE Aerospace Conference, Aspen, Colorado, paper no. 168, 1999

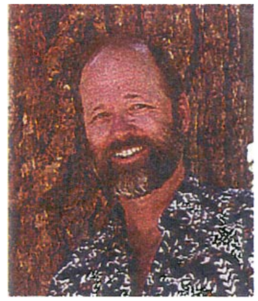
[3] M. Matson and J. Dozier, "Identification of Subresolution High Temperature Sources Using a Thermal IR Sensor," *Photogrammetric Engineering and Remote Sensing* **47**:1311-1318, 1981

[4] W. L. Wolfe and G. J. Zissis (eds.), *The Infrared Handbook,* Ann Arbor, Michigan: The Infrared Information Analysis Center, Environmental Research Institute of Michigan, 1978

[5] R A. Wood,. "High-Performance Infrared Thermal Imaging with Monolithic Silicon Focal Planes Operating at Room Temperatures," *Proceedings IEDM.,* Washington DC., December 6, 1993

ACKNOWLEDGEMENTS

This research was supported by a Research Joint Venture Agreement between Space Instruments, Inc., and the Pacific Southwest Research Station, USDA Forest Service; by the USDA Forest Service, International Programs; and by the U. S. Agency for International Development. Trade names, commercial products, and enterprises are mentioned solely for information. No endorsement by the U.S. Department of Agriculture is implied.



Philip Riggan is a scientist with the USDA Forest Service, Pacific Southwest Research Station, at the Forest Fire Laboratory in Riverside, California. He holds a Bachelor of Science degree in chemistry from San Diego State University and a Ph.D. from the College of Forest Resources at the University of Washington. His research has included development of technology for remote sensing of the dynamics of wildland fires, the impact of atmospheric deposition and fire severity on watershed processes, and the potential effects of wildland and agricultural fires on global climate change. Since 1991 he has led a bilateral program of the Forest Service and the Brazilian Federal Institute of the Environment and Natural Resources (IBAMA) that is assessing impacts of fire and environmental change in tropical forest and savanna of Brazil.

James Hoffman has been Technical Director for Space Instruments, Inc., since 1980. He has over 25 years of experience in the design of electro-optical instruments for remote sensing and surveillance. He earned a B.E.E. degree from Cornell University and a M.S.E.E. degree from the University of Hawaii. He has been the principal investigator on contracts developing the Infrared Spectral Imaging Radiometer, the Thermal Imaging Radiometer, the NASA Cloud Top Radiometer and Earth Radiation Array, and Hi-Camp II. Previously he was a Senior Systems Engineer for Hughes Aircraft Company where he was systems engineer for the design of the Landsat Thematic Mapper. He received a DARPA Strategic Technology Office Special Award in 1987.

James Brass is a research scientist and remote sensing specialist with the NASA Ames Research Center. He received from the University ofMinnesota a Bachelor of Science degree in Forest Resources and a Master of Science degree in Forest Resources and Remote Sensing. His current research interests are the measurement of wildland fires and development of technological systems for natural disaster assessment. He received NASA National Achievement Awards in 1988, 1989, and 1991.