SUPPLEMENTARY MATERIALS TO BE SUBMITTED WITH MANUSCRIPT AS ACCESSORY PUBLICATIONS

Accessory Publication 1

Calibration procedure for single-band WASP LWIR data - incorporating spectral sensor response and atmospheric transmission

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We describe a calibration approach providing total ground-leaving radiative excitance (W m^{-2}), also termed fire radiated flux density (FRFD), from the response of a limited-bandpass infrared sensor. The resulting calibration relationships are specific to individual fires because spectral atmospheric transmission data are incorporated. Here we report calibration relationships for the RxCADRE 2011 and 2012 WASP data collections. Calibration of the WASP longwave infrared (LWIR) sensor (8 to 9.2 µm nominal bandpass) (Fig. AP1-1) involves relating total ground-leaving radiance (W m^{-2} sr^{-1}) from 0.1 to 20 µm (accounting for almost all fire radiation) to

WASP raw output (digital number, DN) through a number of linked steps. The general calibration equation is

$$L_T = bL_{LWIR}{}^{M} \qquad (1)$$

where L_T (W m^{-2} sr^{-1}) is total ground-leaving radiance; L_{LWIR} is detector-reaching radiance in the passband of the WASP LWIR detector during flights over wildland fires; and *b* and *M* are parameters relating restricted-bandpass to total radiance. The inclusion of a unit solid angle in steradians for dimensional consistency is implied (see Palmer and Grant 2009, eq. 2.32). The WASP Indigo Phoenix LWIR camera (model IA126 LWIR) was built by Cantronic Systems Incorporated and has quantum-well, cooled detectors. The WASP LWIR camera has 14 bits of dynamic range and is cooled by a Stirling cooler to about 60°K.

The first step in the calibration process is to relate DN to calculated blackbody radiance in the bandpass of the sensor. For calibration measurements, the blackbody and WASP sensor were placed well off the floor and surrounding areas wrapped in foil to avoid background effects on calibration measurements. The distance between the blackbody and sensor was set so that the blackbody filled more than 40 central pixels. In this near extended–source configuration (NES) (Palmer and Grant 2009, section 7.6.4), the blackbody is close enough to the sensor so that pixels are much smaller than the heated area and radiance reaching the front of the lens is equal to blackbody radiance. The average of pixel DN for a given blackbody temperature is calculated for only the central region of the blackbody where temperatures are uniform. A swing-in blackbody calibrator that is now used during WASP operation and shows that there is minimal drift in DN associated with camera lens temperature variation during flights. The image of the blackbody was flat-fielded to account for known variation in sensor response across the field of view. A 2-

ms integration time was used in WASP flight operations in order to avoid saturation yet provide as much background radiance information as possible during fire imaging missions.

Radiance leaving the blackbody and causing a response by the detector (detector-reaching radiance, L_{LWIR}) is a function of blackbody temperature and emissivity along with properties of the sensor. L_{LWIR} is determined over a range of blackbody temperatures (280–1601°K) through integration of Planck's radiation law,

$$L_{LWIR} = \varepsilon t_L \int_0^{\lambda_{max}} f(T, L_\lambda, R_\lambda) \qquad (2)$$

where the integral is evaluated from 0 μm to λ_{max} (20 μm), ε is blackbody emissivity (0.95), t_L is proportional transmission of infrared radiation through the lens (0.98), T is blackbody temperature (K), L_λ is spectral radiance (W m^{-2} μm^{-1} sr^{-1}), and R_λ is proportional sensor spectral response (Fig. AP1-1). L_{LWIR} is then related to DN, which is a second-order polynomial in the case of the WASP longwave infrared sensor (Fig. AP1-2):

$$L_{LWIR} = f(DN) = 2x10^{-6}DN^2 + 0.0176DN \qquad (3)$$

The parameters b and M relating L_T to L_{LWIR} in Eqn 1 are estimated from the output of 10,000 simulations of total radiative excitance from mixed-temperature fire pixels (Kremens and Dickinson 2014) (Fig. AP1-3). Estimates of total and restricted bandpass (i.e., LWIR) excitance were based on randomly generated assemblages of 30 sub-pixel areas representing the pre-frontal fuel bed, the flaming front, and the zone of post-frontal combustion and cooling. Different sub-pixel areas are defined by their temperatures and emissivities. Total excitance from these sub-pixel areas was calculated from the Stefan-Boltzmann Law and summed to give L_T. L_{LWIR} is calculated as in Eqn 2, but with the additional effect of atmospheric absorption so that it represents WASP LWIR detector-reaching radiance during overflights:

$$L_{LWIR} = \varepsilon t_L \int_0^{\lambda_{max}} f(T, L_\lambda, R_\lambda, A_\lambda) \qquad (4)$$

where A_λ is atmospheric spectral transmission calculated from MODTRAN (Table AP1-1, Fig. AP1-4).

Combining Eqns 1 and 3 and converting to excitance (W m^{-2}) by multiplication of both sides of the question by π, the form of the final calibration equation for ground-leaving excitance is $P_T = \pi b\left(f(DN)\right)^M$ where b and M are given in Table 1 for individual fires.

References

Kremens RL, Dickinson MB (2014) Estimating radiated flux density from wildland fires from the raw output of restricted-bandpass detectors. *International Journal of Wildland Fire*, in review.

Palmer JM, Grant BG (2010) Radiometric measurement and calibration. In 'The art of radiometry'. pp. 241-268 (SPIE Press: Bellingham, WA). doi: 10.1117/3.798237

Table AP1-1. Average atmospheric absorption estimated from MODTRAN for the large 2011 and 2012 burns. Atmospheric profile data used in MODTRAN are from soundings collected from balloons launched before ignition. Relative humidity is averaged from the surface to 3000 m. Flight altitude used was representative of the VIIRS and MODIS overpass times. Parameters *b* and *M* from Eqn 1 are estimated from a power-law fit to untransformed data because this approach, in contrast to linear regression on log-log transformed data, resulted in the least bias in background fire radiative flux density (FRFD).

Fire	Date	Launch time (UTC)	Air temperature (°K)	Relative humidity (%)	Ignition time (UTC)		Flight altitude (m)	Average transmission (8-9.2 μm)	b	M
					Start	End				
703C	06 February 2011	15:00	280	28	18:24	19:02	3030	0.88	2.955	1.397
608A	08 February 2011	14:50	285	37	18:25	19:55	2250	0.90	2.880	1.399
L1G	04 November 2012	20:31	300	48	18:30	19:46	3155	0.71	4.158	1.412
L2G	10 November 2012	20:10	296	47	18:03	21:00	3160	0.75	3.947	1.403
L2F	11 November 2012	21:49	297	50	18:23	19:05	1550	0.76	3.753	1.409

Fig. AP1-1. Spectral response of the WASP longwave infrared sensor. The nominal bandpass of the sensor is 8–9.2 µm, approximately the full width of the spectral response at 50% response (full width at one-half maximum)(FWHM).

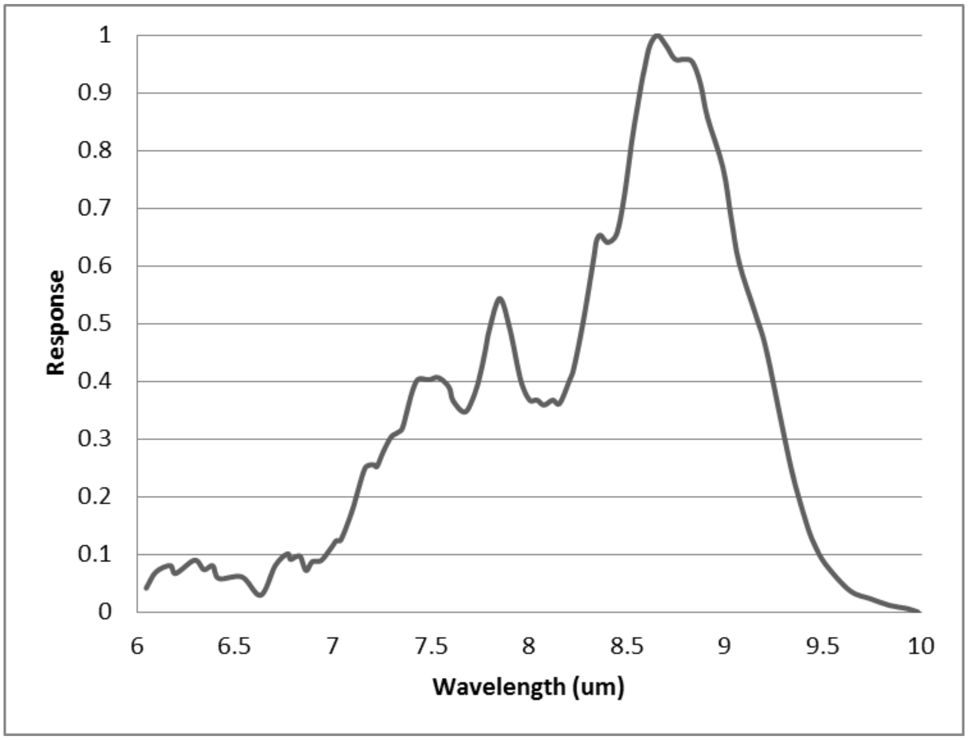

Fig. AP1-2. Calibration relationship for radiance in the WASP longwave infrared passband determined from laboratory blackbody calibration (closed circles) and three field measurements (open circles). Field measurements are average WASP background DN during three fires and detector-reaching radiance estimated for the WASP passband at the observed air temperature (see above). The polynomial regression fit only included blackbody data.

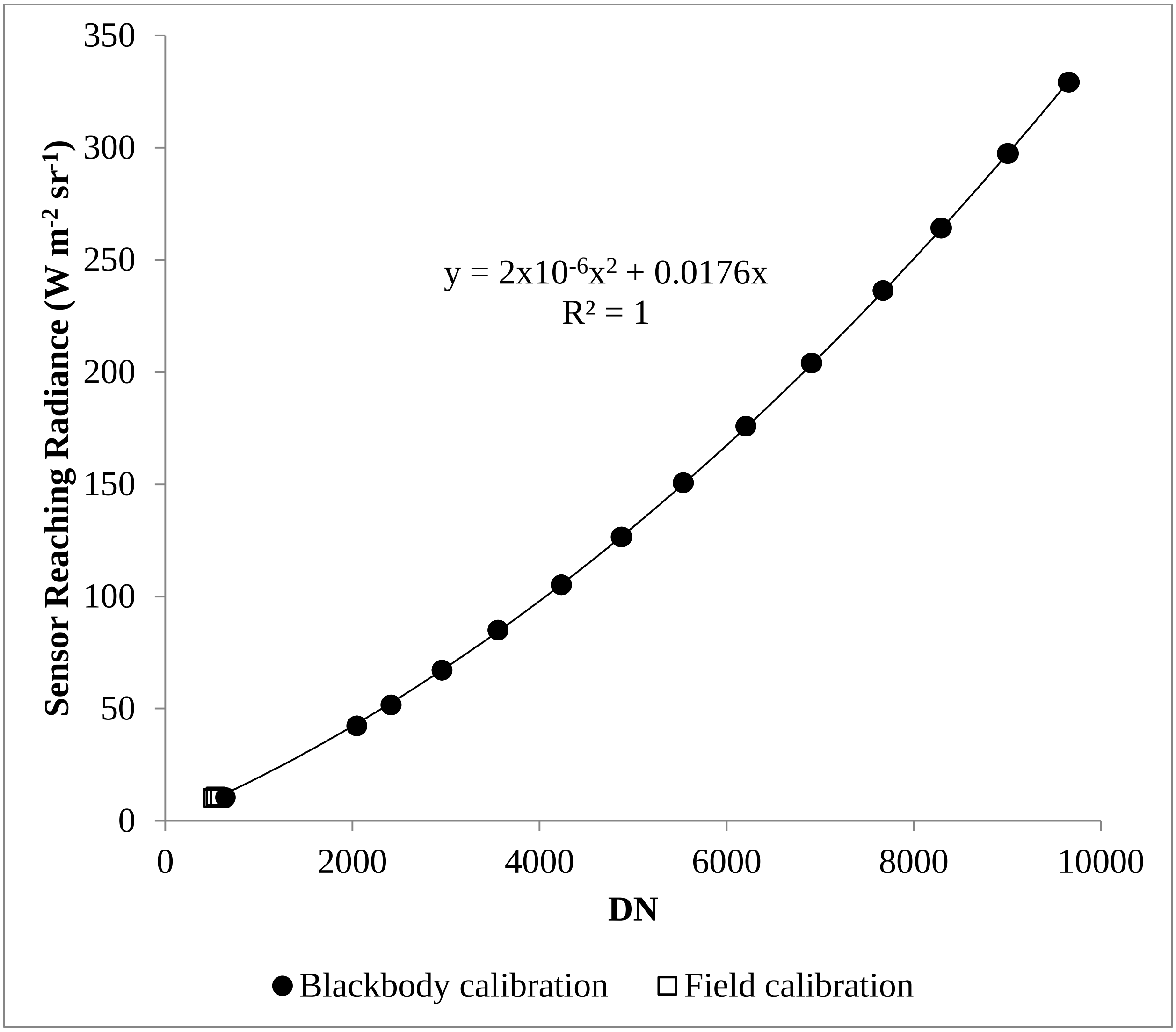

Fig. AP1-3. Power-law relationship between untransformed (total) ground-leaving and detector-reaching radiance for L2F from 10,000 fire pixel simulations. Results for other fires were similar (Table 1).

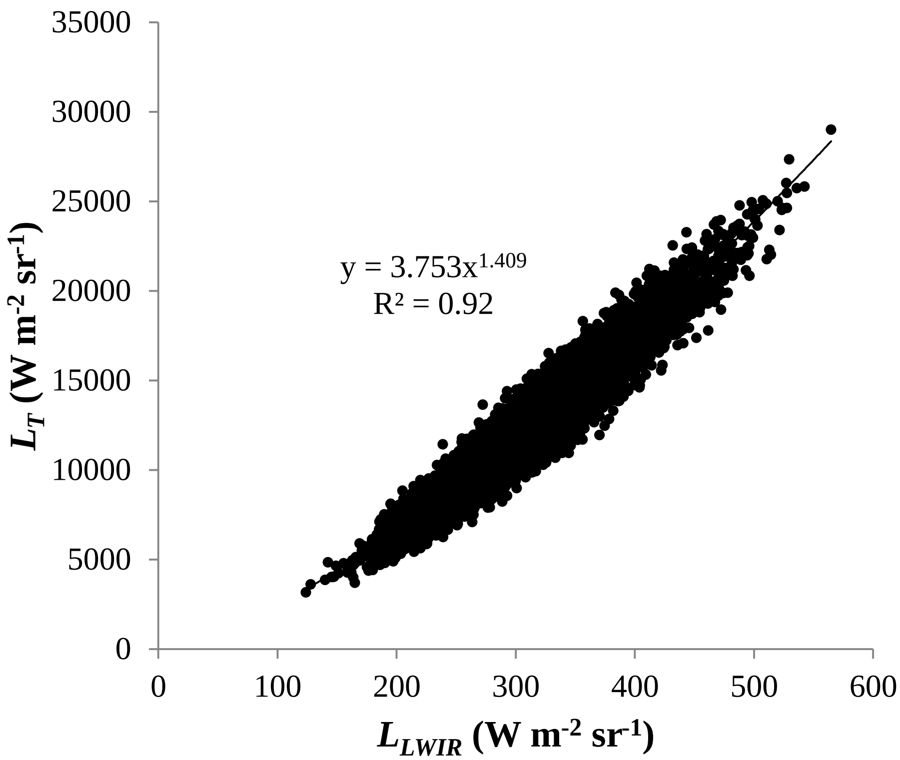

Fig. AP1-4. MODTRAN spectral atmospheric transmission for L2F based on an atmospheric profile from a mid-morning sounding conducted prior to ignition (see Table AP1-1).