August 31, 1995

To: Bruce Guenther
Harry Montgomery

From: Dan Knowles

Subject: MODIS ATBD 1995: radiometric calibration algorithm for the thermal bands

Reference:
"MODIS infrared calibration algorithm derivation for ATBD 1995: draft", by Dan Knowles, August 7, 1995.
"Effects of low emissivity regions in using the on-board calibrator blackbody", by Dan Knowles and Ed Knight, March 2, 1995.
"OBC BB polarization", by Dan Knowles and Ed Knight, June 7, 1995.
"MODIS 1995 ATBD thermal calibration hybrid approach: traditional versus universal curve", by Dan Knowles, August 21, 1995.
"Radiometric averaging versus thermal averaging of the OBC blackbody", by Dan Knowles, August 23, 1995.
"Two-point calibration of non-linear PC HgCdTe channels", Infrared Phys. Technol. 36, by I. L. Goldberg, 1995.
"Gain Coefficients for radiometric calibration: version 2", PL3095-M03082, by Tom Pagano, October 4, 1993.

Attached is this is the first draft of the MODIS ATBD 1995: radiometric calibration algorithm for the thermal bands. Included within the uncertainty analysis is the ghosting results from Shi-Yue Qiu. Time permitting, Qiu's scattering results will also be included.

The equations included within this document are derived in the first referenced memo. Eq. 1 of this memo is Eq. 1 of the referenced memo. Eq. 2 of this memo is Eq. 27 of the referenced memo. Eq. 3 of this memo is Eq. 60 of the referenced memo.

MODIS ATBD 1995: Radiometric Calibration Algorithm for the Thermal Bands

Draft: August 31, 1995 by Dan Knowles

Summary

The MODIS Level 1B calibration algorithm for the thermal bands is designed to determine the apparent spectral radiance (with associated uncertainties) for each pixel observed through the Earth view. To track on-orbit changes in the instrument, the thermal bands will be recalibrated every scan. Improvements over the 1994 ATBD involve detector nonlinearity, scan mirror reflectivity variations with scan angle, optical background corrections and pre-launch testing requirements. Some issues under current consideration with details pending are polarization and spurious effects.

Top-Level Algorithm

This algorithm is essentially a hybrid of the SBRC approach and the historically accepted approaches, with the key difference being the accountability of optical background and nonlinearity on-orbit. This accountability is made possible through both the DC restore offset voltage, which has not previously been available in the telemetry of other satellites and the optics and detector thermistors measurements. This additional telemetry will make it possible to transform the electronic counts of the instrument into the focal plane voltage V_{fpa}. In its basic form, the algorithm is based on the relationship between V_{fpa} and the total power applied to the detector (Fig. 1 and Eq. 1).

$$V_{fpa} = a(\Phi_s + P_{back})^2 + b(\Phi_s + P_{back}) \tag{1}$$

This relationship is assumed quadratic for the somewhat limited range of detector incident radiant power. The background power term P_{back} is an extrapolation to the zero voltage condition, which includes the power attributed to the detector bias voltage and the detector incident radiant flux due of the thermal state of the optics. Φ_s represents the detector incident radiant flux attributed to any arbitrary source external to the fold mirror. a and b are the second and first order detector gain terms respectively.

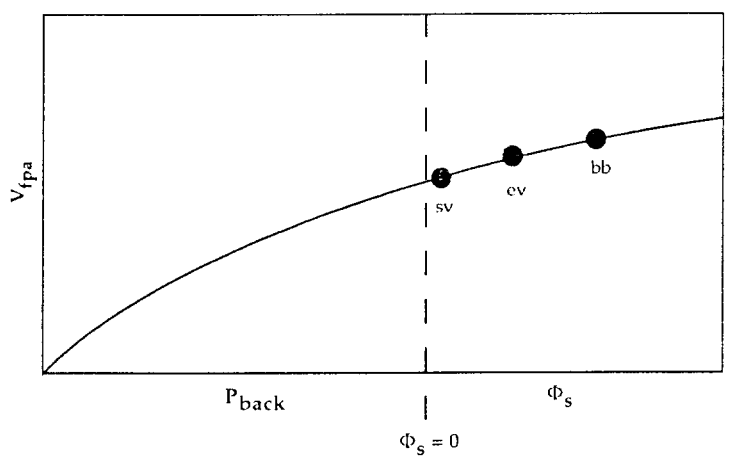

Fig 1. Thermal band calibration curve

For simplicity of notation to this document, detector irradiance will be treated as monochromatic. However, the actual equations will be integrated across the spectral response of the band. Expressing Eq. 1 in terms of scene radiance yields the thermal algorithm (Eq. 2), where a new set of gain coefficients is determined.

$$V_{fpa} = \alpha m^2 (L_o + \delta_0 \rho_0 (L_s - B_{mir}))^2 + m(L_o + \delta_0 \rho_0 (L_s - B_{mir})) \tag{2}$$

The background power term L_o as well as the first order gain coefficient m are determined every scan from the OBC blackbody and space view measurements. The second order gain coefficient α is treated per detector on-orbit as a function of detector temperature, instrument temperature, and mirror side based on pre-launch measurements. Three calibration sources (BCS, SVS, and OBC blackbody) will be used to determine on-orbit values of α. Fig. 2 portrays the temperature conditions for the current protoflight test plan (check marks denote planned tests). δ_0, which is the OBC blackbody scan angle relative reflectivity of the scan mirror, is measured while viewing space through the Earth view during a spacecraft maneuver. Associated with this maneuver technique, 1/f noise is a significant factor in detecting variations in the scan mirror emission with angle, permitting only the LWIR bands to be scan angle corrected. ρ_0 is the scan angle dependent absolute reflectivity of the scan mirror. L_s is the apparent scene radiance and B_{mir} is the Planck function evaluated at the scan mirror temperature.

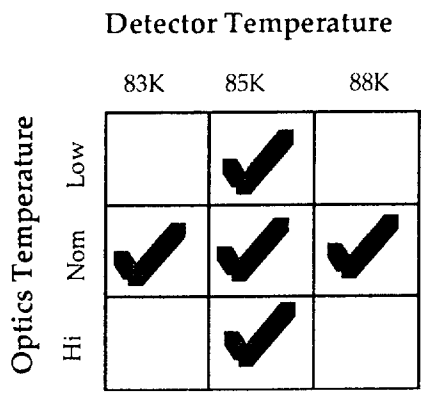

Fig 1. Current Protoflight Test Plan

Space View

The space view is the cold (zero scene radiance) calibration source. However, there will be some nonspecular radiance from the scan mirror while scanning the space view and a correction term for possible scan cavity edge contributions will be included. If the BRDF of the scan mirror is well understood, the correction term can be adjusted based on the cavity temperature local to the space view.

15 space view signals will be available each scan for calibration. An outlier rejection routine is planned to eliminate bad data caused by cosmic items and electronic burps. A limit will be set pertaining to the number of frames which can be rejected for normal calibration. Because up to 30 space view signals are used to determine an effective space view signal, many of these signals will fall below the effective signal. This is natural because the effects of noise have been somewhat negated from the effective signal. This brings about the paradox of possible negative radiance calibration products of cold Earth scenes. This is permissible as long as the uncertainty bars include a value sufficient to make the radiance calibration product zero. Exceptions will be appropriately flagged.

OBC Blackbody

The OBC blackbody is the warm calibration source. The radiance of the OBC blackbody incident upon the scan mirror can be expressed by Eq. 3.

$$L_{bb} = \varepsilon_{bb} B_{bb} + \frac{1-\varepsilon_{bb}}{\pi}(\Omega_{cav} B_{cav} + \Omega_{ev} B_{Earth}) \tag{3}$$

ε_{bb} is the emissivity of the OBC blackbody. Ω_{cav} is the effective solid angle of the scan cavity subtended at the blackbody and Ω_{ev} is the effective solid angle of the Earth view porthole visible to the blackbody. B_{bb}, B_{cav}, and B_{Earth} is the Planck function of the OBC blackbody, MODIS scan cavity, and visible portion of the Earth respectively.

The twelve OBC blackbody thermistors will be averaged to obtained one effective temperature for the blackbody. This is possible because the expected gradients will be small and the focal plane "footprint" covers about 90% of the blackbody for any single data sample. Fifteen OBC blackbody data frames will be available each scan for calibration. An outlier rejection routine is planned for the OBC blackbody data frames as well as for the thermistors due to possible thermistor failure. These outliers will be monitored and flagged if a pattern is detected.

The effective temperature of the scan cavity must be determined from appropriate thermistors within the scan cavity. This will be done by weighted averages of the radiance determined from each of the pertinent scan cavity thermistors (exact algorithm and thermistors are TBD). The effective radiance of the Earth is a fairly minor term in Eq. 3 (less than 1 part in a thousand). This radiance is at the average temperature of the entire Earth scene (value is TBD) which directly illuminates the surface of the on-board blackbody.

The temperature of the OBC blackbody can be elevated to 315K and subsequently cooled down to ambient. This would present a possibility for the on-orbit determination of the nonlinear calibration term. However, due to the nonisothermal nature of this scenario, optical background drifts will occur and it will be a nontrivial "at best" effort to account for these drifts. The thermal calibration equation places no restriction on the OBC blackbody temperature and can be calibrated identically for both the normal and heated operational blackbody modes. However, a warning flag will be affixed to the data acquired during the heated mode.

The emissivity of the OBC blackbody might not be directly measured. If this is the case, measurements of the substrate material will be used to determine the OBC blackbody emissivity. The current opinion for determining the OBC blackbody emissivity in this manner is to assume that 10% of the radiance achieves only a single bounce, while the remaining radiance achieves four bounces within the v-groove surfaces. Current analyses shows that the on-board blackbody has a small but possibly significant residual polarization which may drop the desired blackbody emissivity below .992 for some MODIS bands.

The BCS will be used to test and further characterize the OBC blackbody (i.e. determining the OBC emissivity, etc.). This algorithm is TBD pending the methodology of these measurements. Ideally the temperature of the BCS would be adjusted to produce approximately the same signal as that of the OBC blackbody. This situation would bypass the requirement for knowledge of the detector non-linearities when calculating the OBC blackbody emissivity. Furthermore, the instrument temperature must be measured (ideally at several temperatures) to characterize the reflective components of the OBC blackbody.

Traceability to NIST of the OBC blackbody temperature will be done directly through the OBC blackbody thermistors. Traceability of the OBC blackbody emissivity will be done through the thermistors of the BCS.

<u>Scan Mirror Reflectivity</u>

The reflectivity of the scan mirror for each detector, mirror side, scan angle, and polarization state is needed for the thermal calibration algorithm. Some of this may be measured by SBRC, or data will possibly be obtained from witness sample testing. The most important measurements pertain to the pre-launch and on-orbit calibrator angles of incidence. The other angular measurements may be derived from this data.

A spacecraft maneuver is currently planned whereby the entire Earth view port can achieve a clear view of space. This provides a hot radiance source (OBC blackbody) and a cold source (view of space through the Earth view porthole) at identical angles of incidence. Therefore, scan angle independent calibration coefficients can be used to determine the scan mirror correction factor δ_0 for both Earth view and space view angles of incidence. This value will be averaged over many scans to reduce the effects of 1/f noise. This correction factor is relative to the blackbody angle of incidence. Because the thermal calibration algorithm is designed to calibrate out the absolute reflectivity of the scan mirror at the blackbody view angle, this correction factor provides an on-orbit means to account for scan mirror reflectivity angular variation due to contamination and pre-launch measurement error.

Noise Reduction

To reduce 1/f noise in the OBC blackbody and the space view, each will be temporally aligned with the Earth scene signal through a linear interpolation routine. This interpolation will be done using the same side of the scan mirror to avoid reflectance complications.

Data Requirements

The data requirements for the calibrator interpolation routine require the current scan *scan i* and the scan occurring two scans later *scan i + 2*. Therefore, if data fails for *scan i + 2*, then *scan i* cannot be calibrated according to the standard baseline approach. For this event, a single scan calibration approach could be used with an appropriate flag.

Electronic Calibration and DC Restore

In order to subtract off redundant optical background detector irradiance, MODIS uses an offset voltage based on the digital output while viewing space. This enables the A/D converter to stay on scale. This aspect of DC restore is executed every scan line based upon data from the previous scan line. Electronic gains are applied to the focal plane voltages based upon the digital output while viewing the OBC blackbody and space. This enables the dynamic range of the 12 bit A/D converter to be used to its potential. These applied gains will not be changed every scan, but will be changed periodically as needed. Because of these on-orbit electronic adjustments, it is necessary to convert the digital counts, gains, and offset voltages into the focal plane voltage. This will enable pre-launch measurements to be incorporated in the on-orbit calibration algorithm. A/D converter responsivity coefficients will be measured pre-launch and possibly on-orbit.

Spectral Calibration

The primary factor in the spectral shape of the optical transmission is the band pass filter. Ideally the spectral shape of the whole system should be measured for each detector's optical path. The measurement methodology is currently TBD.

Polarization

Because the polarization of the scan mirror significantly increases with angle of incidence, the polarization of Earth samples acquired towards the end of the Earth scan will become an increasing factor. Polarization coefficients will be necessary to account for this effect. If the apparent radiance from the Earth scene is polarized and this polarization is understood, the polarization coefficients can be set to more accurately determine the calibration product. Otherwise, the polarization coefficients will default to an unpolarized apparent Earth scene (Exact equations TBD). The OBC blackbody is also polarized, and will be another key facet to this algorithm.

Adverse Calibration Events

Lunar illumination of the space view will render the space view temporarily useless as a zero based calibration source. By monitoring the offset voltage and digital counts of the space view independent of ephemeris data, it is possible to determine when the moon is visible through the

space view porthole. These scans can be calibrated by freezing the calibration coefficients from the scan just before the lunar effect occurs. This calibration must be appropriately flagged.

By tracking both the OBC blackbody and the space view voltages, it is possible to determine whether the reflected OBC blackbody radiance increases as the solar diffuser is illuminated. If possible, an algorithm will be developed to account for this increase in reflected OBC blackbody radiance. SRCA operations can also affect thermal calibration. This will most likely be less significant than the solar diffuser illumination, however, the technique for correcting for this will be similar.

Spurious Effects

Spurious effects can occur one of two possible ways: 1) while viewing the calibration source, in which case the calibration coefficients are affected, 2) during the Earth scene scan, in which case these effects are implemented after the calibrated Earth scene spectral radiance is determined.

Ghosting effects, optical scattering effects, and within-band optical crosstalk should have little effect on the calibration coefficients. While scanning the OBC blackbody, which has a minimal thermal gradient, the image of the OBC fills the entire focal plane, with each detector receiving about 60% of the total uncollimated blackbody rays. While scanning space, each detector images 1.4 mrad of space, and unless some substantial cosmic item is present, this region can be considered uniform. However, if an outlier space view signal is found, then the temporal signals from other bands might also be considered outliers subject to rejection. Out of band crosstalk when viewing the blackbody will need to be analyzed

Spurious effects which occur during the Earth view scan are substantial. Of these effects, scattering appears to be the most significant. A model which simulates the effects of ghosting and scattering has been developed and a model for crosstalk effects is planned. From this analysis, the near-field scattering will most likely drive all bands out of specification (TBD). Ghosting analysis at 4 km from cloud edge shows some of the bands are slightly out of specification. Once these spurious effects are well simulated, the algorithm can be adjusted to remove these effects.

Vicarious Calibration

In order to use a vicarious source, the apparent Earth scene radiance determined from digital counts and the OBC calibrators, must sufficiently agree with the external determination of that apparent radiance. For the symmetrical blackbody scan angle and an Earth scene close to the OBC blackbody radiance, this check will be most accurate. If done early in the flight mission, and proven reliable, later vicarious measurements can be utilized to possibly correct for OBC emissivity changes and nonlinearity changes. The details for this methodology are currently TBD

Radiometric Uncertainties

A model of the MODIS instrument was produced to generate MODIS output using realistic nominal parameters. The calibration algorithm was then applied to this data with expected errors perturbed in each of the unrelated calibration parameters. An RSS of these individual errors then gave a means for an analysis of the thermal calibration error.

Table 1 shows the RSS results for all the MODIS bands compared with the MODIS specification. These results are by no means definitive for uncertainties of many individual parameters have not been established yet. Included within this analysis are effects of: OBC blackbody temperature, OBC blackbody emissivity, scan cavity temperature, scan mirror temperature, nonlinearity, digitization, 1/f noise, center wavelength, scan mirror relative reflectivity, DC restore, and ghosting. Scattering and crosstalk are not currently included within these results.

MODIS Band	Radiometric Error*	Radiometric Error**	MODIS Spec
20	2.16%	0.78%	0.8%
21	6.91%	6.65%	10.0%
22	1.98%	0.74%	1.0%
23	1.91%	0.72%	1.0%
24	3.26%	0.98%	1.0%
25	1.74%	0.82%	1.0%
27	2.35%	1.03%	1.0%
28	1.41%	0.79%	1.0%
29	0.46%	0.42%	1.0%
30	1.24%	1.02%	1.0%
31	0.31%	0.27%	0.5%
32	0.33%	0.23%	0.5%
33	0.61%	0.39%	1.0%
34	0.70%	0.39%	1.0%
35	0.84%	0.41%	1.0%
36	1.33%	0.57%	1.0%
31hi	9.81%	9.80%	10.0%
32hi	4.74%	4.72%	10.0%

Table 1. Current Predicted Radiometric Uncertainties in percent of Ltyp

* scan mirror relative reflectivity uncertainty = .4% and center wavelength uncertainty = .25%

* *scan mirror relative reflectivity uncertainty = .1% and center wavelength uncertainty = .025%

Part of the Level 1B product will be the uncertainties for each calibrated Earth scene pixel. This will be achieved by perturbing each of the algorithm parameters by an appropriate amount (pertinent to the MODIS specification and other pre-launch measurements) whereby an Earth scene radiance error can be compared with the unperturbed Earth scene calibrated radiance. A root sum square of all these perturbations will yield an uncertainty unique to every Earth scene pixel.