Electronic Supplement 2

Calibration

Calibration allows the Digital Number (DN) recorded by the A/D converter to be converted to the sensor recorded radiance (R*). This is typically achieved through a linear conversion which has the form given in Chapter 2, i.e.,:

$$R^* = a\,DN + b$$

in which a and b are the scaled slope and intercept of the straight line relation between R* and DN. However, in some cases the relationship is non-linear. In addition, the method of calculating the slope and intercept varies from sensor to sensor. We illustrate these complications here by considering the calibration for the three main sensors in each class: TM, AVHRR and GOES.

A note on radiance units and conversion to temperature using the Planck function

The units of radiance output by the conversion given above will vary depending on the units of the calibration coefficients used for the DN to R* conversion. For example, calibration coefficients for Landsat TM are in units of mW cm^{-2} sr^{-1} μm^{-1}. Hence TM radiance values are in the same units. Calibration coefficients for AVHRR and GOES, however, are in units of milliwatts / m^2-steradian-cm^{-1}. As described in Chapter 2, this must be remembered when applying the Planck Function to convert radiance to temperature. For example, we can utilize Equation (2.5) of Chapter 2 to convert TM radiances to temperatures. However, the radiance units input into Equation (2.5) must be W m^{-2} m^{-1}. Thus, as described in Chapter 2, wavelength must be input into Equation (2.5) in meters (so that 12 μm = 12 × 10^{-6} m) and radiance values must be multiplied by 10^7 to convert to units of W m^{-2} sr^{-1} m^{-1}, and then by π to obtain W m^{-2} m^{-1}, so that:

$$\begin{aligned} 23.463\ \mathrm{mW\ cm^{-2}\ sr^{-1}\ \mu m^{-1}} &= 23.463\ \mathrm{mW\ cm^{-2}\ sr^{-1}\ \mu m^{-1}} \times 10^7 \times 3.14 \\ &= 7.37 \times 10^8\ \mathrm{W\ m^{-2}\ m^{-1}} \end{aligned}$$

Likewise, Equation (2.6b) is of the correct form to use with radiance units of milliwatts/ m^2-steradian-cm^{-1}, and wavelength must be input in units of cm^{-1}.

TM Calibration

TM digital numbers range between 0 and 255. These are related to R* (in units of mW cm^{-2} sr^{-1} μm^{-1}) following a linear conversion. The form of this relationship, as defined by Markham and Barker (1986; 1987), is given by:

$$R^* = LMIN_\lambda \left(\frac{LMAX_\lambda - LMIN_\lambda}{255} \right) + DN$$

in which $LMIN_\lambda$ and $LMAX_\lambda$ are constants used in TM ground processing that reflect the minimum radiance at DN=0 and maximum radiance at DN=255. The calibration coefficients provided by Markham and Barker (1986; 1987) are given here in Table S2.1. Also given in Table S2.1 are the radiances that these coefficients give at the minimum and maximum recordable DNs, and the temperature equivalents of these radiances. These radiance and temperature ranges define the dynamic range of each detector.

Drift and error

Calibration can drift with time. Thus, being a pre-launch calibration which is fixed and constant from orbit to orbit, there may be some difference between the radiance obtained from the pre-launch calibration, and the true radiance to which the post-launch DN relates. As a result, some differences have been found between the radiance obtained using pre-launch calibration, and post-launch radiances expected on the basis of field measurements. For example, using data collected at White Sands (USA) between July 1984 and November 1985, Slater et al. (1987) found uncertainty in the calibration of Landsat's NIR and SWIR bands by ±2.8 %. Likewise, cross-checks by Schott and Volchok (1985) between ground truth data and Landsat 5 TM data acquired over Lake Ontario on 22 June 1984 revealed a systematic error in TIR band temperatures. This was consistent with an excess gain factor of about 1.64 for band 6. This is equivalent to a maximum error in retrieved temperature of 4 °C (for the DN=255 radiance). As is apparent from Table S2.1 calibration did change with time, with the latest update being achieved through cross-calibration with ETM+ data by Chandler and Markham (2003). Thus retrieved radiance may be in error by a few percent.

Primary information sources

Chander, G., and Markham, B. (2003). Revised Landsat-5 TM radiometric calibration procedures and postcalibration dynamic ranges. *IEEE Transactions in Geoscience and Remote Sensing*, **41**(11), 2674–2677.

Markham, B. L., and Barker, J. L. (1986). Landsat MSS and TM post-calibration dynamic ranges, exoatmospheric irradiances and at-satellite temperatures. *EOSAT Landsat Technical Notes*, **1**, 3–8

Markham, B. L., and Barker, J. L. (1987). Thematic Mapper bandpass solar exoatmospheric irradiances. *International Journal of Remote Sensing*, **8**(3), 517–523.

Table S2.1. *TM calibration coefficients, DN of minimum and maximum radiance (DN_{min} and DN_{max}), with the minimum and maximum radiances and temperatures that these give.*

TM Post-Calibration Coefficients: Prior to August 1983 (Markham & Barker, 1986)

TM Band	Wavelength (m)	$LMIN_\lambda$ (mW cm^{-2} sr^{-1} μm^{-1})	$LMAX_\lambda$	DN_{min}	DN_{max}	R^*_{min} (mW cm^{-2} sr^{-1} μm^{-1})	R^*_{max}	T_{min}, (°C)	T_{max} (°C)
3	6.60E-07	−0.117	23.463	2	255	0.067941176	23.463	762	1160
4	8.30E-07	−0.151	22.432	2	255	0.026121569	22.432	558	956
5	1.65E-06	−0.037	3.242	3	255	0.001576471	3.242	158	418
6	1.15E-05	0.2	1.564	1	255	0.20534902	1.564	−52	68
7	2.22E-06	−0.015	1.7	3	255	0.005176471	1.7	96	278

TM Post-Calibration Coefficients: Prior to 15 Jan 1984 (Markham & Barker, 1986)

TM Band	Wavelength (m)	$LMIN_\lambda$ (mW cm^{-2} sr^{-1} μm^{-1})	$LMAX_\lambda$	DN_{min}	DN_{max}	R^*_{min} (mW cm^{-2} sr^{-1} μm^{-1})	R^*_{max}	T_{min}, (°C)	T_{max} (°C)
3	6.60E-07	0	22.5	1	255	0.088235294	22.5	775	1156
4	8.30E-07	0	21.429	1	255	0.084035294	21.429	607	952
5	1.65E-06	0	3	1	255	0.011764706	3	205	414
6	1.15E-05	0.484	1.24	1	255	0.486964706	1.24	−13	49
7	2.22E-06	0	1.593	1	255	0.006247059	1.593	100	275

TM Post-Calibration Coefficients: After 15 Jan 1984 (Markham & Barker, 1986)

TM Band	Wavelength (m)	$LMIN_\lambda$ (mW cm^{-2} sr^{-1} μm^{-1})	$LMAX_\lambda$	DN_{min}	DN_{max}	R^*_{min} (mW cm^{-2} sr^{-1} μm^{-1})	R^*_{max}	T_{min}, (°C)	T_{max} (°C)
3	6.60E-07	−0.12	20.43	2	255	0.041176471	20.43	738	1147
4	8.30E-07	−0.15	20.62	2	255	0.012901961	20.62	531	948
5	1.65E-06	−0.037	2.719	4	255	0.006231373	2.719	189	409
6	1.15E-05	0.1238	1.56	1	255	0.129432157	1.56	−69	68
7	2.22E-06	−0.015	1.438	3	255	0.002094118	1.438	78	270

TM Post-Calibration Coefficients: After 5 May 2003 (Chander & Markham, 2003)

TM Band	Wavelength (m)	$LMIN_\lambda$ (mW cm^{-2} sr^{-1} μm^{-1})	$LMAX_\lambda$	DN_{min}	DN_{max}	R^*_{min} (mW cm^{-2} sr^{-1} μm^{-1})	R^*_{max}	T_{min}, (°C)	T_{max} (°C)
3	6.60E-07	−0.117	26.4	2	255	0.090976471	26.4	777	1171
4	8.30E-07	−1.51	22.1	17	255	0.064	22.1	595	954
5	1.65E-06	−0.037	3.02	4	255	0.010952941	3.02	203	415
6	1.15E-05	0.12378	1.5303	1	255	0.129295765	1.5303	−69	66
7	2.22E-06	−0.015	1.65	3	255	0.004588235	1.65	94	277

Schott, J. R., and Volchok, W. J. (1985). Thematic Mapper thermal infrared calibration. *Photogrammetric Engineering and Remote Sensing*, **51**(9), 1351–1357.
Slater, P. N., Biggar, S. F., Holm, R. G., Jackson, R. D., Mao, Y., Moran, S., Palmer, J. M. and Yuan, B. (1987). Reflectance- and radiance-based methods for the in-fligh absolute calibration of multispectral sensors. *Remote Sensing of Environment*, **22**, 11–37.

AVHRR Calibration

AVHRR digital numbers range between zero and 1024. These are related to radiance following a linear conversion. The slope and intercept values for AVHRR's IR channels can be determined using a two point calibration that uses deep space and an on-board blackbody. Because these data are collected during each scan, the slope and intercept can be calculated from data collected during each mirror sweep (see Chapter 3). Unlike TM, AVHRR images thus have an image-specific calibration, so that the calibration is always current. Following Lauritson et al. (1979), slope (in units of radiance per count) can be obtained from these data using:

$$a = (N_T - N_{sp}) / (X_T - X_{sp})$$

in which N_T is the radiance recorded when the instrument views its internal calibration target (of known temperature and radiance) and N_{sp} is the radiance recorded for deep space (which should be zero if the detector response is linear). X_T and X_{sp} are the mean counts (DN) associated with several observations of space and the internal target. The intercept is then obtained from:

$$b = N_{sp} + a\,X_{sp}$$

These data can be found in the image header file, where the header file format, location of these data, and how to calculate coefficients a and b are given by Kidwell (1991; 1995).

Now DN is converted to sensor recorded radiance (R*, in units of milliwatts/steradian-m^2-cm^{-1}) via

$$R^* = a\,DN + b$$

For AVHRR, maximum recordable radiance is obtained at DN=0 and the minimum recordable radiance is obtained at DN=1024. Thus, AVHRR's calibration is inverse, i.e., increasing radiance results in decreasing DN.

Calibration coefficients calculated from the header files of images obtained from AVHRR flown on NOAAs -9, -11, -12 and -14 are given in Table S2.2. Also given in Table S2.2 are the radiances that these coefficients give at the minimum and maximum recordable DN, plus the temperatures to which these relate. From Table S2.2 we see that the slope and intercept does vary from sensor to sensor, resulting in a difference between the retrieved temperature by a few degrees, as revealed by comparing the T_{max} for each case. For a single satellite, there is also some drift over time. This is apparent from Table S2.2 which gives two calibration coefficients for band 4 of NOAA-9: the first obtained towards the beginning

Table S2.2. *Typical AVHRR calibration coefficients calculated from the header files of images obtained by the AVHRR flown on NOAAs-9, -11, -12 and –14. Also given are DN of minimum and maximum radiance (DN_{min} and DN_{max}), with the minimum and maximum radiances and temperatures that these give. Central wavenumbers for each band are from Kidwell (1991; 1995).*

AVHRR-Calibration Coefficients: Band 3

NOAA	Central wavenumber (cm^{-1})	Slope	Intercept	DN_{min}	DN_{max}	R^*_{max} ($mW\ m^{-2}\ sr^{-1}\ cm^{-1}$)	R^*_{min} ($mW\ m^{-2}\ sr^{-1}\ cm^{-1}$)	T_{min}, (°C)	T_{max} (°C)
9	2678.11	−0.00144	1.43277	0	990	1.43277	0.00618	−52.0	48.5
11	2671.4	−0.0015	1.480445	0	985	1.480445	0.006258	−52.4	48.8
12	2640.817	−0.00166	1.6457	0	990	1.6457	0.00527	−56.5	48.9
14	2647.169	−0.0016	1.589785	0	990	1.589785	0.00232	−65.9	48.5

AVHRR-Calibration Coefficients: Band 4

NOAA	Central wavenumber (cm^{-1})	Slope	Intercept	DN_{min}	DN_{max}	R^*_{max} ($mW\ m^{-2}\ sr^{-1}\ cm^{-1}$)	R^*_{min} ($mW\ m^{-2}\ sr^{-1}\ cm^{-1}$)	T_{min}, (°C)	T_{max} (°C)
9[a]	929.46	−0.15953	157.64085	0	985	157.6409	0.50577	−137.3	51.3
9[b]	929.46	−0.15474	152.880065	0	985	152.8801	0.463135	−138.5	49.0
11	927.8	−0.1802	178.98093	0	985	178.9809	1.48227	−120.9	61.3
12	921.2741	−0.16392	162.940495	0	990	162.9405	0.659695	−134.4	53.1
14	929.5878	−0.16222	156.89655	0	965	156.8966	0.352803	−142.1	51.0

[a] NOAA-9 calibration for image obtained on 11/04/86

[b] NOAA-9 calibration for image obtained on 12/12/94

Note (1): Slope is in units of $\frac{miliwatts/m^2 - steradian - cm^{-1}}{DN}$

Note (2): Intercept is in units of milliwatts / m^2-steradian-cm^{-1}

Note (3): NOAA-9 data = 12/12/94 image

Note (4): NOAA-11 data = mean from 22 images spanning 15/12/91 to 05/08/94

Note (5): NOAA-12 data = 15/08/93 image

Note (6): NOAA-14 data = mean from 4 images spanning 22/01/95 to 18/07/95

of the sensor lifetime in 1986, the second towards the end in 1994. We see a decrease in both the slope and intercept over the lifetime of the sensor, so that retrieved T_{max} is almost 3 °C lower by 1994. Likewise, a comparison of calibration coefficients over a three year period for NOAA-11, as given in Table S2.3, shows variation in the slope and intercept which causes retrieved T_{max} in channel 4 to vary by 5 °C. Variation is less in channel 3, where T_{max} differs by only 0.1 °C.

Table S2.3. *AVHRR calibration coefficients calculated from the header files of 22 images obtained by the AVHRR flown on NOAA-11 between 15 December 1991 and 5 August 1994.*

NOAA-11 AVHRR-Calibration Coefficients: Band 3

Date	Slope	Intercept	DN_{min}	DN_{max}	R^*_{max} (mW m^{-2} sr^{-1} cm^{-1})	R^*_{min} (mW m^{-2} sr^{-1} cm^{-1})	T_{min}, (°C)	T_{max} (°C)
15/12/91	−0.00149	1.478514	0	985	1.478514	0.006924	−51.0	48.8
24/12/91	−0.0015	1.482797	0	985	1.482797	0.006282	−52.3	48.8
24/02/92	−0.0015	1.480637	0	985	1.480637	0.007077	−50.7	48.8
10/05/92	−0.0015	1.483727	0	985	1.483727	0.007212	−50.5	48.8
03/06/92	−0.0015	1.486389	0	985	1.486389	0.005934	−53.0	48.9
17/08/92	−0.0015	1.481076	0	985	1.481076	0.006531	−51.8	48.8
11/09/92	−0.0015	1.482266	0	985	1.482266	0.005751	−53.4	48.8
30/10/92	−0.0015	1.486188	0	985	1.486188	0.006718	−51.4	48.9
24/11/92	−0.0015	1.482638	0	985	1.482638	0.006123	−52.6	48.8
06/02/93	−0.0015	1.48233	0	985	1.48233	0.0068	−51.3	48.8
11/03/93	−0.0015	1.483295	0	985	1.483295	0.00678	−51.3	48.8
29/03/93	−0.0015	1.483751	0	985	1.483751	0.006251	−52.3	48.8
13/04/93	−0.0015	1.480714	0	985	1.480714	0.006169	−52.5	48.8
21/04/93	−0.0015	1.479175	0	985	1.479175	0.0066	−51.6	48.8
01/06/93	−0.0015	1.479578	0	985	1.479578	0.007003	−50.9	48.8
25/06/93	−0.0015	1.481058	0	985	1.481058	0.006513	−51.8	48.8
13/12/93	−0.0015	1.478928	0	985	1.478928	0.005368	−54.2	48.8
05/03/94	−0.0015	1.478541	0	985	1.478541	0.005966	−52.9	48.8
14/04/94	−0.00149	1.473713	0	985	1.473713	0.005078	−54.9	48.7
26/06/94	−0.00149	1.473713	0	985	1.473713	0.004093	−57.6	48.7
04/07/94	−0.00149	1.47411	0	985	1.47411	0.00646	−51.9	48.7
05/08/94	−0.00149	1.478514	0	985	1.478514	0.006924	−51.0	48.8
Mean	−0.0015	1.480445	0	985	1.480445	0.006258	−52.4	48.8

NOAA-11 AVHRR-Calibration Coefficients: Band 4

Date	Slope	Intercept	DN_{min}	DN_{max}	R^*_{max} (mW m^{-2} sr^{-1} cm^{-1})	R^*_{min} (mW m^{-2} sr^{-1} cm^{-1})	T_{min}, (°C)	T_{max} (°C)
15/12/91	−0.17759	176.356795	0	985	176.3568	1.42966	−121.5	60.1
24/12/91	−0.17762	176.383399	0	985	176.3834	1.431639	−121.5	60.1
24/02/92	−0.17727	176.035711	0	985	176.0357	1.422791	−121.6	60.0
10/05/92	−0.1771	175.871348	0	985	175.8713	1.424893	−121.5	59.9
03/06/92	−0.17644	175.222200	0	985	175.2222	1.43077	−121.5	59.6
17/08/92	−0.17748	176.235885	0	985	176.2359	1.422025	−121.6	60.1
11/09/92	−0.17874	177.499240	0	985	177.4992	1.445265	−121.3	60.6
30/10/92	−0.1803	179.046198	0	985	179.0462	1.453653	−121.2	61.4

NOAA-11 AVHRR-Calibration Coefficients: Band 4 (*cont.*)

Date	Slope	Intercept	DN_{min}	DN_{max}	R^*_{max} (mW m^{-2} sr^{-1} cm^{-1})	R^*_{min}	T_{min}, (°C)	T_{max} (°C)
24/11/92	−0.17991	178.655618	0	985	178.6556	1.446238	−121.3	61.2
06/02/93	−0.17923	177.984317	0	985	177.9843	1.440797	−121.4	60.9
11/03/93	−0.1798	178.556173	0	985	178.5562	1.455143	−121.2	61.1
29/03/93	−0.1801	178.845073	0	985	178.8451	1.446573	−121.3	61.3
13/04/93	−0.17992	178.658113	0	985	178.6581	1.441838	−121.3	61.2
21/04/93	−0.17989	178.633334	0	985	178.6333	1.441684	−121.3	61.2
01/06/93	−0.18266	182.076505	0	985	182.0765	2.156405	−114.1	62.7
25/06/93	−0.17849	177.243865	0	985	177.2439	1.433185	−121.4	60.5
13/12/93	−0.18461	183.321847	0	985	183.3218	1.480012	−120.9	63.3
05/03/94	−0.18497	183.679015	0	985	183.679	1.485535	−120.8	63.5
14/04/94	−0.18687	185.569774	0	985	185.5698	1.506764	−120.6	64.3
26/06/94	−0.18115	179.900625	0	985	179.9006	1.469845	−121.0	61.7
04/07/94	−0.18117	179.919185	0	985	179.9192	1.470675	−121.0	61.8
05/08/94	−0.18316	181.886161	0	985	181.8862	1.474546	−121.0	62.7
Mean	−0.1802	178.98093	0	985	178.9809	1.48227	−120.9	61.3

Non-linear response

AVHRR's response in bands 4 and 5 is actually slightly non-linear. This was first pointed out in a 5 June 1978 memo from the AVHRR sensor branch. In this, Goldberg (1978) stated that "*the non-linear response of a photoconductor such as HgCdTe can be explained with the help of semiconductor theory*" which "*is very complex*". Suffice to say, corrections were subsequently published to allow a non-linearity correction to be applied to AVHRR's two TIR bands (bands 4 and 5), these being the two AVHRR bands that use HgCdTe detectors. The actual relationship between DN and R* for an HgCdTe detector was given by Goldberg (1978) as:

$$DN = a + b\,R^* + c\,(R^*)^2$$

in which a, b and c are empirically determined parameters which vary with detector temperature. The memo of Goldberg (1978) was followed up by an information note led by Nelson (1978) in which an initial non-linearity correction to TIROS-N data was suggested for AVHRR's 11 μm channel:

$$R^* = 164.2900694 - 0.1740367527\,DN + 8.5109E\text{-}06\,DN^2$$

Brown et al. (1985), subsequently found "*a weak, but important dependence in calibration upon internal operating temperature*". Thus, Weinreb et al. (1990) published a procedure whereby a correction was applied depending on the base-plate, or internal calibration target, temperature and scene temperature. The corrections proposed by Weinreb et al. (1990) are given for the AVHRR aboard NOAA-9 in Table S2.4. In this case, brightness temperature obtained from R* using the linear conversion (T*) is corrected for non-linearity to give a corrected temperature (T^{nl}). This is achieved by adding the correction term for the appropriate scene and base-plate temperature to T*, i.e.:

$$T^{nl} = T^{*} + NC$$

Thus, for a scene temperature of 319 K, obtained at a base-plate temperature of 15 °C, the correction from Table S2.4 is,

$$T^{nl} = 319\ K + 2.53\ K = 321.53\ K$$

and for a scene temperature of 215 K, obtained at a base-plate temperature of 10 °C,

$$T^{nl} = 215\ K\ -\ 1.22\ K = 213.78\ K$$

Table S2.4 also serves as a look up table for the error resulting from failure to take into account the non-linearity effect. For NOAA 9 (at a base-plate temperature of 15 °C), this ranges from an underestimate in the band 4 temperature by ~2.5 K for a scene temperature of

Table S2.4. *Nonlinearity correction terms (NC) for the AVHRR aboard NOAA-9 derived by Weinreb et al. (1990) from the difference between the true calibration and the linear approximation.*

	Internal Target Temperature (°C)					
	Channel 4			Channel 5		
Scene Temperature (K)	10.0	15.0	19.3	10.0	15.0	19.3
320	2.35	2.53	2.28	0.82	1.14	1.16
315	1.89	1.97	1.81	0.64	0.83	0.91
310		1.55	1.31		0.71	0.68
305	1.45	1.02	0.88	0.66	0.35	0.47
295	0.82	0.46	0.17	0.45	0.20	0.09
285	0.11	−0.22	−0.48	0.05	−0.09	−0.24
275	−0.48	−0.61	−0.90	−0.25	−0.31	−0.47
265	−0.71	−0.84	−1.26	−0.42	−0.46	−0.75
255	−0.96	−1.25	−1.50	−0.63	−0.81	−0.91
245	−1.09	−1.36	−1.66	−0.76	−0.92	−1.12
235	−1.15	−1.38	−1.60	−1.03	−1.19	−1.31
225	−1.32	−1.39	−1.53	−1.14	−1.11	−1.14
215	−1.22	−1.34	−1.42	−1.24	−1.28	−1.41
205	−1.21	−1.48	−0.90	−1.43	−1.62	−1.23

320 K, to an overestimate in the band 4 temperature by ~1.5 K for a scene temperature of 205 K.

Brown et al. (1993) re-parameterized the correction, publishing a correction with a polynomial form:

$$NC = a_0 + a_1 T^* + a_2 (T^*)^2$$

in which a_0, a_1 and a_2 are least squares fit coefficients between the linear calibration-obtained temperature and the real temperature. These correction procedures were adopted by Kidwell (1995) who gave appropriate coefficients for each AVHRR sensor. The coefficients given by Brown et al. (1993) for band 4 of the AVHRR aboard NOAAs -9, -11 and -12 are given here in Table S2.5. Using the Table S2.5 coefficients, for a band 4 scene temperature of 319 K (= 45.85 °C) in AVHRR data from NOAA-9, we obtain a correction of,

$$NC = 0.13803 + 0.067867 \times (45.85\ °C) + 0.00067669 \times (45.85\ °C)^2 = 4.7\ °C$$

so that

$$T^{nl} = 45.85\ °C + 4.7\ °C = 50.5\ °C = 323.7\ K$$

For a scene temperature of 215 K (= −58.15 °C), we obtain

$$NC = 0.13803 + 0.067867 \times (-58.15\ °C) + 0.00067669 \times (-58.15\ °C)^2 = -1.5\ °C$$

so that

$$T^{nl} = -58.15\ °C - 1.5\ °C = -59.7\ °C = 213.5\ K$$

These two results can be compared with the corrections based on the procedure of Weinreb et al. (1990) as given above.

In Table S2.6 we apply the correction of Brown et al. (1993) to the minimum and maximum recordable temperatures for NOAAs -9, -11 and –12. We find that, by taking into account the non-linear response, the maximum recordable band 4 temperature is actually 5 to 10 °C higher than that expected from the linear calibration, increasing the apparent upper detection limit of the sensor.

Table S2.5. *Non-linearity correction coefficients for AVHRR band 4 given by Brown et al. (1993).*

NOAA	a_0	a_1	a_2	R^2
9	1.3803E-1	6.7867E-2	6.7669E-4	0.998
11	1.8636E-1	1.0257E-1	9.2111E-4	0.998
12	1.7889E-1	6.4893E-2	4.7233E-4	0.983

Table S2.6. *Minimum and maximum recordable temperatures in AVHRR band 4 calculated for NOAAs-9, -11 and -12 in Table S2.2 using the linear DN to Radiance conversion. These are compared with those obtained from application of the non-linear correction of Brown et al. (1993).*

	Linear Calibration		Non-Linear Correction	
NOAA	T_{min}, (°C)	T_{max}(°C)	T_{min}, (°C)	T_{max}(°C)
9[a]	−137.3	51.3	−133.7	56.8
9[b]	−138.5	49.0	−134.8	54.1
11	−120.9	61.3	−119.7	71.3
12	−134.4	53.1	−134.4	58.1

[a] NOAA-9 calibration for image obtained on 11/04/86
[b] NOAA-9 calibration for image obtained on 12/12/94

MODIS

MODIS Level 1B data come ready calibrated. The calibration routine is similar to that of the AVHRR and involves use of deep space and on-board blackbody targets viewed during each scan to define a DN to radiance conversion on a scan-by-scan basis. The conversion is scan angle dependent, is performed for each band and detector, and includes a correction for scan mirror emission, as detailed in Xiong et al. (2005).

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GOES Calibration

GOES DN are in the range 0 to 1023, and convert to a radiance following a positive, linear relationship, so that increasing DN relate to increasing radiance. GOES infrared image data are transmitted in GVAR (GOES VARiable Format), where a memo by Weinreb et al. (2006) describes how GVAR format DN are converted to radiance and brightness temperature. First, DN is converted to radiance (R* in mW / m^2 sr cm^{-1}) following:

$$R^* = (DN - b) / a$$

in which a and b are the slope and intercept of the linear relationship between radiance and DN. Pre-launch slope and intercept values for GOES Images are given in Table S2.7. The radiances and effective temperatures that the minimum and maximum DN convert to are also given in Table S2.7. Being HgCdTe detectors, the GOES infrared bands also require correction for non-linearity, whereby

$$R^* = q\,DN^2 + a\,DN + b$$

the non-linearity correction (q) being set (as with the AVHRR) depending on instrument operating and detector temperature. These corrections are all carried out as part of the GVAR processing so that the user is supplied with processed, calibrated and corrected radiance data.

As described by Weinreb (1997), calibration coefficients are calculated in a similar fashion to the AVHRR, where data from a spacecraft based blackbody and space allow the slope and intercept to be calculated on a regular basis. As a result, real calibration coefficients may diverge from the pre-launch values given in Table S2.7. The blackbody (bb) and space (sp) data are used to calculate the slope of the calibration relationship from:

$$a = \frac{R_{bb} - q({X_{bb}}^2 - {X_{sp}}^2)}{X_{bb} - X_{sp}}$$

in which R_{bb} is the blackbody radiance, and X_{bb} and X_{sp} are the mean counts (DN) associated with several observations of the internal blackbody and space. Now,

$$b = -a\,X_{sp} - q\,{X_{sp}}^2$$

For the GOES imager, space based calibration is made every 2.2 to 36.6 seconds, and blackbody calibration is made every 30 minutes, with X_{sp} being the 400 sample average for

Table S2.7. *GOES-Imager calibration coefficients from Weinreb et al. (2006).*

GOES-Imager Calibration Coefficients: Bands 2 and 4

Band	Slope	Intercept	DN_{min}	DN_{max}	R^*_{min} (mW m^{-2} sr^{-1} cm^{-1})	R^*_{max} (mW m^{-2} sr^{-1} cm^{-1})	T_{min}, (°C)	T_{max} (°C)
2	227.3889	68.2167	70	1023	0.00784251	4.1989	−57.0	69.1
4	5.2285	15.6854	20	1023	0.82520799	192.6584	−129.8	68.0

Table S2.8. *Conversion from effective temperature obtained using the central wavelength of the sensor in the Planck Function(T_{eff}) to temperature (T) expected from a conversion that involves convolution of the Planck function across bands 2 and 4 of the GOES 12 Imager (following the method of Weinreb et al., 2006).*

GOES-12 Imager-Calibration Coefficients: Bands 2 and 4

Band	Central wavelength (cm^{-1})	T_{eff} (min) °C	T_{eff} (max) °C	α	β	T (min) °C	T (max) °C
2	2562.45	−57.0	69.1	v0.650731	1.00152	−57.3	69.0
4	933.21	−129.8	68.0	−0.360331	1.001306	−130.0	68.1

the space looks preceding and following the blackbody view, and X_{BB} being an average of 1000 samples acquired during the blackbody view (Weinreb et al., 1997).

Convolution of Planck and spectral response functions

As will be shown in Electronic Supplement 3, precise brightness temperature retrieval requires convolution of the Planck Function and sensor spectral response function. So far in this Supplement, the wavelength of the band mid-point has been used in the Planck Function to complete a conversion from radiance to brightness temperature. For band 2 of the Imager aboard GOES-12 the use of the central wavelength of 3.9 μm (2562.45 cm^{-1}) in the Planck Function with the maximum recordable radiance, as given in Table S2.7, yields a T_{max} of 69.1 °C. However, the Planck Function will vary across the waveband which extends from 3.8 μm (2631.58 cm^{-1}) to 4.0 μm (2500.00 cm^{-1}). Using these two wavelengths with the maximum recordable radiance, for example, yields T_{max} of 75.8 °C and 63.1 °C, respectively. It is thus important to use the correct wavelength and/or assess whether convolution of the appropriate spectrally dependent values is necessary (see Electronic Supplement 3).

Weinreb et al. (2006) provide a short-cut that takes into account variation in the Planck function across each GOES waveband. Temperatures calculated using the central wavelength of each waveband are termed effective temperatures (T_{eff}). These are related to the temperature (T) obtained by convolving the Planck Function across the waveband in question using a best-fitting approach between T and T_{eff} for the full range of temperatures that the GOES sensor is capable of detecting. The resulting relationship has the form:

$$T = \alpha + \beta\ T_{eff}$$

where values for α and β, calculated by Weinreb et al. (2006) for bands 2 and 4 of the Imager aboard GOES-12, are given in Table S2.8. As shown in Table S2.8, the correction, in this case, involves an adjustment of a few 10ths of a degree centigrade. Indeed, Weinreb et al. (2006) state that the difference between the values of T and T_{eff} are usually of the order of 0.1 K, with differences increasing with decreased temperature so that, in the worst case, the difference is ~0.3 K near 180 K. This is similar to the conclusion of Electronic Supplement 3, where we will find that a band averaged (central wavelength) approach applied to MODIS Band 22 yields tempratures that are within 0.1 K of those obtained from convolution of the Planck Function and sensor response function, as well as emissivity and atmospheric spectra, across the waveband.

Primary information sources

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