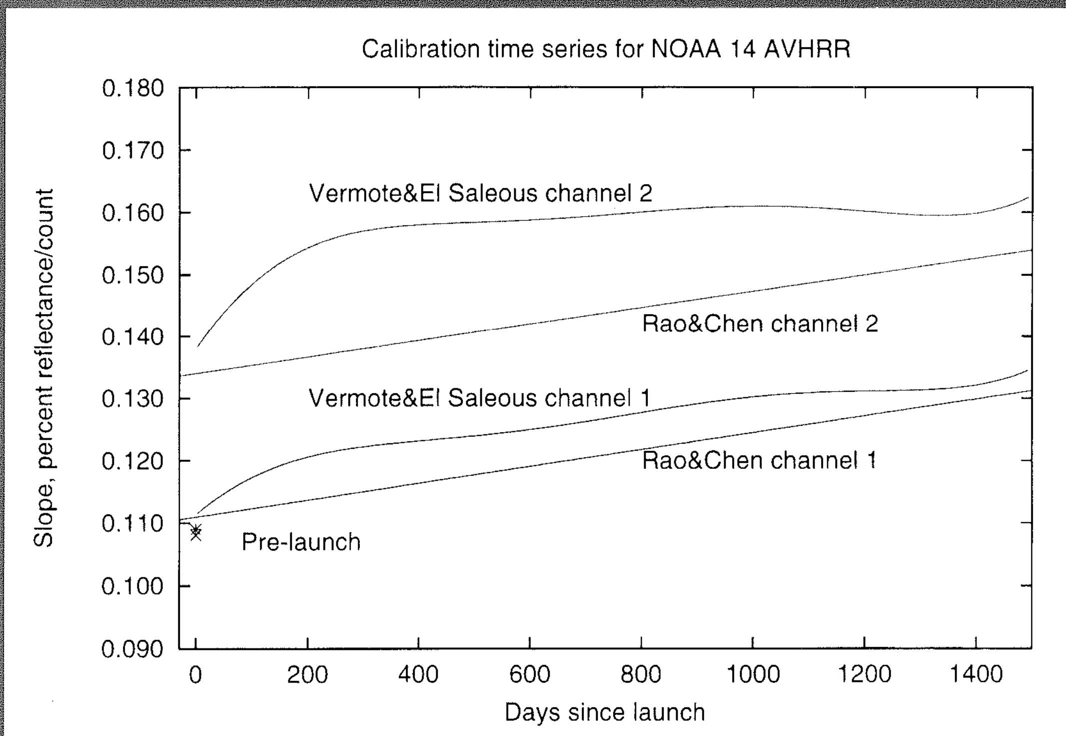
Calibration Status of the NOAA AVHRR Solar Reflectance Channels: CalWatch Revision 1

R.M. Mitchell



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Abstract

The solar reflectance channels on the NOAA AVHRR instrument have no on-board calibration source and are known to drift in sensitivity following launch. Various methods have been developed for the post-launch calibration of these channels. This document brings together the results of this work in a form suited to the operational calibration of AVHRR data sets from both historical and currently operational sensors. The CalWatch project aims to provide users of the AVHRR solar reflectance channels with a set of calibration coefficients maintained centrally, enabling uniform generation of higher level products across the user community. Accordingly, direct electronic access is provided to the data tables appearing in this document so that processing software can be furnished with current calibration coefficients.

1 Introduction

Advanced Very High Resolution Radiometers (AVHRR) have been flown on successive NOAA polar orbiting satellites over the last two decades, since the launch of NOAA 6 in 1979. The two solar reflectance channels on these instruments were originally intended primarily for qualitative applications such as cloud detection and land-sea discrimination, so no on-board calibration facility was provided. However, these channels have since found wide ranging applications far exceeding design expectation. One example is the attempt to monitor changes in land surface on a variety of timescales. Whilst clearly useful on seasonal and interannual timescales, the goal of change detection over decadal timescales requires precise knowledge of sensor calibration spanning several different instruments if apparent changes are to be assigned with confidence to the surface rather than to sensor drift. This issue was brought into sharp focus by the recent work of Myneni *et al.* (1997), where a secular greening at northern latitudes was inferred from a time series of AVHRR images.

To address this issue, a considerable effort has been expended by a number of workers over the last decade. Techniques developed include the use of congruent path aircraft underflights (Abel *et al.* 1993), stable desert targets (Staylor 1990; Teillet *et al.* 1990; Rao and Chen 1995), ocean targets (Kaufman and Holben 1993; Mitchell *et al.* 1992, 1996; Vermote and Kaufman 1995) and intercalibration of the two channels using bright clouds (Vermote and Kaufman 1995) and desert sites (Los 1998). Further description of these and other methods may be found in Teillet and Holben (1994) or Mitchell *et al.* (1996).

The results tabulated below represent a selection from among these methods based on the author's view of their accuracy, utility and likelihood of continuation. The selection is inevitably somewhat subjective, but is based on the best information available to the author at the time of publication.

2 Conversion from digital counts to radiance and reflectance

2.1 Definitions

Radiometric calibration refers to the mapping between instrument response in digital counts and the radiance at the instrument aperture. This radiance may be further expressed as a reflectance factor, through normalization by the solar irradiance as detailed below.

In-band radiance The instrument responds to the upwelling radiance integrated over the spectral bandpass of the relevant channel. This in-band radiance is defined as

$$\overline{I}_i = \int_0^\infty d\lambda \phi_i(\lambda) I(\lambda)$$

where $\phi_i(\lambda)$ is the instrument spectral response function and $I(\lambda)$ is the spectral radiance at the instrument aperture.

Mean spectral radiance It is usual to define a mean spectral radiance on the basis of the measured in-band radiance as

$$I_i = \frac{\overline{I}_i}{w_i}$$

where w_i is the effective width of the spectral bandpass,

$$w_i = \int_0^\infty d\lambda \phi_i(\lambda).$$

Reflectance factor It has become common practice to express the instrument radiance as a reflectance factor. This factor is defined as the ratio of the upwelling irradiance over a lambertian surface that would produce the measured in-band radiance, to the irradiance of the extraterrestrial solar beam, ie

$$R_i = \frac{100\pi \overline{I}_i}{\overline{F}_i(r)} \tag{1}$$

where R_i is expressed in percent and $\overline{F}_i(r)$ is the extraterrestrial solar irradiance integrated over the spectral bandpass of channel i. It is important to distinguish the reflectance factor from higher level products such as the top of atmosphere directional reflectance, defined as

$$r_i = \frac{\pi \overline{I}_i}{\overline{F}_i(r) \cos\theta_0}$$

where $\cos\theta_0$ is the solar zenith angle.

Note that for a constant in-band radiance, the reflectance factor varies during the year owing to the ellipticity of the earth's orbit about the sun. This seasonal variation can be expressed

$$\overline{F}_i(r) = \overline{F}_i(1\text{AU}) r^{-2}$$

where $\overline{F}_i(1\text{AU})$ is the in-band extraterrestrial solar irradiance at one astronomical unit (AU), and r is the sun-earth distance in AU, given by

$$r = 1.00014 - 0.01671 \cos g - 0.00014 \cos 2g \tag{2}$$

where g is the mean anomaly given in degrees by

$$g = (0.9856003 d_{1975} - 2.97394) \bmod 360 \tag{3}$$

where d_{1975} is the number of days elapsed since noon UT on December 31, 1974, so that at noon UT on January 1, 1975, d_{1975}=1. The annual cycle in the extraterrestrial solar irradiance is approximately $\pm 3\%$ about the mean.

2.2 AVHRR/2 (up to and including NOAA 14)

In-band radiance The digital count recorded by the instrument is taken to be a monotonic linear function of the in-band radiance at the instrument aperture, that is,

$$C_i = C_{0i} + g_i\overline{I}_i$$

where i is the channel number, C_{0i} is the space count corresponding to the instrument response for zero radiance, $\overline{I}_i$ is the in-band radiance in $\mathrm{W\,m^{-2}\,sr^{-1}}$ and g_i the in-band radiance responsivity in units of count $(\mathrm{W\,m^{-2}\,sr^{-1}})^{-1}$. Given C_{0i} and g_i, the radiance inferred from response C_i counts is

$$\overline{I}_i = (C_i - C_{0i})g_i^{-1}. \tag{4}$$

Spectral radiance The analagous relation between counts and mean spectral radiance is

$$I_i = (C_i - C_{0i})h_i^{-1}. \tag{5}$$

where I_i has units $\mathrm{W\,m^{-2}\,\mu m^{-1}\,sr^{-1}}$ and hence the spectral radiance responsivity h_i is expressed in units of count $(\mathrm{W\,m^{-2}\,\mu m^{-1}\,sr^{-1}})^{-1}$.

Reflectance factor Following the convention adopted by NOAA, the relation between reflectance factor and digital count is written

$$R_i = (C_i - C_{0i})S_i \tag{6}$$

where the 'slope' parameter S_i is expressed in units of percent reflectance per unit count. From the definition of R_i given in Equation 1, it follows that S_i is a function of sun-earth distance and can be written

$$S_i(r) = S_i(1\mathrm{AU})r^2 \tag{7}$$

where $S_i(1\mathrm{AU})$ is the slope parameter for a sun-earth distance of 1 AU. All tabulations of S_i appearing later in this document are for this configuration.

Note that Equation 6 was traditionally expressed

$$R_i = C_iS_i + J_i$$

where $J_i = -C_{0i}S_i$ was known as the 'intercept'. The use of this form is discouraged since the intercept is not a primary quantity but depends on both slope and space count. The alternative forms (4), (5) and (6) are directly related to the operation of the radiometer.

2.3 Calibration coefficients for AVHRR/3

The solar reflectance channels of the AVHRR/3 instruments on board NOAA K(15), L and M differ from the earlier version in two respects:

- Channel 3 is intended to alternate between 1.6 μm during daylight hours and 3.7 μm during the night. The 1.6 μm channel is known as 'Channel 3a' while the 3.7 μm channel is called 'Channel 3b'.
- The amplifier response characteristic for channels 1, 2 and 3a has been changed to enhance the radiometric resolution at low signal levels. More specifically, for channels 1 and 2, the reflectance range 0–25% now occupies the first half of the digitization range, i.e. nominally 0–511 counts in the total ten-bit range of 0–1023. For channel 3a, the reflectance range 0–12.5% now occupies nominal count range 0–511.

To accommodate this change, two sets of calibration coefficients are required to define the bi-linear response characteristic. In the lower reflectance range, the response is defined by the low reflectance responsivity (g_{li}, h_{li} or S_{li}), where i is the channel number 1,2 or 3a, together with the space count C_{0i}. In this range the radiance and reflectance follow from Equations 4–6 as shown below.

Lower reflectance range

In-band radiance

$$\overline{I}_i = (C_i - C_{0i})g_{li}^{-1} \tag{8}$$

Spectral radiance

$$I_i = (C_i - C_{0i})h_{li}^{-1} \tag{9}$$

Reflectance factor

$$R_i = (C_i - C_{0i})S_{li}. \tag{10}$$

These equations apply over the count range $0 \leq C_i \leq C_{ti}$ where C_{ti} is the transition count in channel i, that is, the count at which the transition from lower to upper response characteristic occurs.

In the upper reflectance range, the response is defined by the upper reflectance responsivity (g_{ui}, h_{ui} or S_{ui}), together with the space count C_{0i} and the transition count C_{ti}. In this range the radiance and reflectance are given by the following expressions.

Upper reflectance range

In-band radiance

$$\overline{I}_i = (C_{ti} - C_{0i})g_{li}^{-1} + (C_i - C_{ti})g_{ui}^{-1} \tag{11}$$

Spectral radiance

$$I_i = (C_{ti} - C_{0i})h_{li}^{-1} + (C_i - C_{ti})h_{ui}^{-1} \tag{12}$$

Reflectance factor

$$R_i = (C_{ti} - C_{0i})S_{li} + (C_i - C_{ti})S_{ui} \tag{13}$$

2.4 Filter characteristics

The following table reports values of the in-band extraterrestrial solar irradiance $\overline{F}_i$(1AU) in W m^{-2} and effective filter width w_i in μm for past and present AVHRR instruments. These data conform with the compilation of Kidwell (1991) and assume the extraterrestrial solar spectrum given by Neckel and Labs (1984).

Satellite	Channel 1		Channel 2		Channel 3a	
	F	w	F	w	F	w
NOAA 7	177.5	0.108	261.9	0.249		
NOAA 8	183.4	0.113	242.8	0.230		
NOAA 9	191.3	0.117	251.8	0.239		
NOAA 10	178.8	0.108	231.5	0.222		
NOAA 11	184.1	0.113	241.1	0.229		
NOAA 12	200.1	0.124	229.9	0.219		
NOAA 14	207.1	0.129	251.01	0.244		
NOAA 15	138.7	0.084	235.4	0.228	10.6	0.044

2.5 Method used to derive space count

A detailed discussion of the AVHRR space count is given in Mitchell (1999). In brief, space count data are transmitted in the HRPT data stream at the rate of ten samples per scan line. In principle the space count should remain invariant at a nominal value near 40 counts throughout the life of the instrument. However, small variations of the order 0.5 count have been observed. Although inconsequential for most applications, these variations are significant for dark target applications such as retrieval of aerosol optical depth over the ocean.

Beginning in August 1992, space count data have been archived and analysed at CSIRO Atmospheric Research using the gaussian fitting method described by Mitchell (1999). For each pass, the mean and standard deviation of the space count is computed. From October 1996, these statistics have been aggregated on a monthly basis. The resulting data are used to determine space count time series appearing in the following tables for sensors operational from 1992 to the present.

2.6 Format and use of calibration data tables

Calibration data are presented separately for each sensor, and are further separated into individual tables for responsivity and spacecount. However, the format for both tables is identical, as follows:

```
Line 1   : NOAA NN where NN is the satellite number
Line 2   : Launch date:  YYYY-MM-DD
Line 3   : Last updated: yyyy-mm-dd
Line 4,5 : Column headings
Line 6+  : Data lines.
```

AVHRR/2

For the AVHRR/2 instruments (NOAA 7 to 14) the data format is as follows:

Valid date range						
First	Last	Item	Order	Channel_1	Channel_2	Source
YYYY-MM-DD	yyyy-mm-dd	IT	M	$p1_0$	$p2_0$	Reference
				$p1_1$	$p2_1$	
				...	...	
				$p1_M$	$p2_M$	

where

First is the first valid date or reference date of the calibration determination

Last is the last valid date of the calibration determination

Item identifies the calibration parameters in the table, and can take on the following values:

- **g** In-band radiance responsivity
- **h** Spectral radiance responsivity
- **S** Slope parameter
- **C0** Space count

Order is the order of the polynomial used to represent the calibration time history.

p_{i_0} is the zero-order coefficient in channel i used to construct the polynomial representation of the calibration quantity $p_i(t)$ from

$$p_i(t) = \sum_{n=0}^{M} p_{i_n}(t - t_0)^n$$

where $t - t_0$ is the time since the reference time in days. For a linear or higher order polynomial, corresponding polynomial coefficients $p_{i_1}, p_{i_2} \ldots p_{i_M}$ are listed on subsequent lines.

Source contains a reference to the source of the information.

AVHRR/3

For the AVHRR/3 instruments (NOAA 15 and beyond) the data format is as follows:

Valid date range							
First	Last	Item	Order	Channel_1	Channel_2	Channel_3a	Source
YYYY-MM-DD	yyyy-mm-dd	ITL	M	$p^l_{1_0}$	$p^l_{2_0}$	$p^l_{3_0}$	Reference
				$p^l_{1_1}$	$p^l_{2_1}$	$p^l_{3_1}$	
				...	...	...	
				$p^l_{1_M}$	$p^l_{2_M}$	$p^l_{3_M}$	
		ITU		$p^u_{1_0}$	$p^u_{2_0}$	$p^u_{3_0}$	
				$p^u_{1_1}$	$p^u_{2_1}$	$p^u_{3_1}$	
				...	...	...	
				$p^u_{1_M}$	$p^u_{2_M}$	$p^u_{3_M}$	

Differences with respect to AVHRR/2 are as follows:

- The column headed `Channel_3a` lists calibration parameters for the 1.6 μm channel
- Coefficients for the lower and upper response ranges of the instrument are listed in successive blocks of the table. The beginning of a block is flagged by the item identifier in column 2, which can take on the following values:

  gL In-band radiance responsivity, lower reflectance range

  gU In-band radiance responsivity, upper reflectance range

  hL Spectral radiance responsivity, lower reflectance range

  hU Spectral radiance responsivity, upper reflectance range

  SL Slope parameter, lower reflectance range

  SU Slope parameter, upper reflectance range

  C0 Space count

  Ct Transition space count.

Calibration parameters for the lower and upper response ranges may be found from

$$p^l_i(t) = \sum_{n=0}^{M} p^l_{i_n}(t - t_0)^n$$

and

$$p^u_i(t) = \sum_{n=0}^{M} p^u_{i_n}(t - t_0)^n$$

respectively.

Hierarchy, extrapolation and electronic access

In the following tables instances will be found where there is more than one polynomial function covering the same time interval. In this case, the recommended function is the one appearing later in the table.

Care should be exercised when applying the tabulated functions at a time beyond the last valid date in the table. There is no assurance as to the accuracy of such extrapolated values. If extrapolation is carried out, then data sets so generated should be suitably flagged.

The web version of this document may be found at

`http://www.dar.csiro.au/rs/calwatch.htm.`

The calibration tables listed below may be obtained by anonymous ftp from `larry.dar.csiro.au` (IP number 138.194.145.65), directory `pub/calwatch/solar`. Files with extension `.res` contain responsivities, while space count data will be found in files with extension `.spa`. The tabulation of filtered extraterrestrial solar irradiances and bandpasses shown in Section 2.4 above will be found in the file `filtflux.tab` in the same directory.

3 Calibration coefficients for past sensors

3.1 NOAA 7

3.1.1 Responsivity

The recommended responsivity time series was obtained by fitting a third-order polynomial to a daily tabulation supplied by Vermote and El Saleous (1999), whose results are based on the ocean method of Vermote and Kaufman (1995).

```
NOAA 07 Responsivity
Launch date:  1981-06-23
Last updated: 1999-03-22
Valid date range
   First        Last    Item Order Channel_1  Channel_2 Source
1978-06-01 1981-06-22 S      0   1.068E-01  1.069E-01 Kidwell(1991)
1981-06-23 1985-01-01 S      3   1.100E-01  1.169E-01 Rao&Chen(1995)
                                 1.111E-05  1.403E-05
                                 5.610E-10  8.417E-10
                                 1.888E-14  3.367E-14
1981-06-23 1985-01-01 S      3   1.105E-01  1.199E-01 Vermote&El Saleous(1999)
                                 6.489E-06  3.549E-05
                                 3.930E-09 -3.054E-08
                                 1.337E-12  1.426E-11
```

3.1.2 Space count

```
NOAA 07 Space count
Launch date:  1981-06-23
Last updated: 1999-03-22
Valid date range
   First        Last    Item Order Channel_1  Channel_2 Source
1978-06-01 1981-06-22 CO     0   3.750E+01  3.960E+01 ITT(1992)
1981-06-23 1981-12-31 CO     1   3.617E+01  3.819E+01 Teillet&Holben(1994)
                                -9.980E-04 -1.561E-03
1982-01-01 1982-12-31 CO     1   3.598E+01  3.789E+01 Teillet&Holben(1994)
                                -7.646E-04 -1.246E-03
1983-01-01 1983-12-31 CO     1   3.570E+01  3.744E+01 Teillet&Holben(1994)
                                -4.588E-04 -8.348E-04
1984-01-01 1984-12-31 CO     1   3.554E+01  3.713E+01 Teillet&Holben(1994)
                                -1.525E-04 -4.226E-04
```

3.2 NOAA 9

3.2.1 Responsivity

The recommended responsivity time series was obtained by fitting a fifth-order polynomial to a daily tabulation supplied by Vermote and El Saleous (1999), whose results are based on the ocean method of Vermote and Kaufman (1995).

```
NOAA 09 Responsivity
Launch date:  1984-12-12
Last updated: 1999-03-22
Valid date range
   First       Last    Item Order Channel_1   Channel_2 Source
1980-02-01 1984-12-11 S      0    1.063E-01   1.075E-01 Kidwell(1991)
1984-12-12 1988-12-31 S      4    1.039E-01   1.136E-01 Rao&Chen(1995)
                                  1.725E-05   1.113E-05
                                  1.432E-09   5.455E-10
                                  7.921E-14   1.782E-14
                                  3.287E-18   4.366E-19
1984-12-12 1988-12-31 S      5    1.005E-01   1.115E-01 Vermote&El Saleous(1999)
                                  1.397E-05   3.613E-05
                                  9.677E-08   6.459E-08
                                 -2.274E-10  -2.334E-10
                                  2.083E-13   2.242E-13
                                 -6.632E-17  -6.991E-17
```

3.2.2 Space count

```
NOAA 09 Space count
Launch date:  1984-12-12
Last updated: 1999-03-22
Valid date range
   First       Last    Item Order Channel_1   Channel_2 Source
1980-02-01 1984-12-11 CO     0    3.900E+01   4.000E+01 ITT(1992)
1984-12-12 1985-12-31 CO     1    3.804E+01   4.007E+01 Teillet&Holben(1994)
                                 -3.872E-04  -1.817E-03
1986-01-01 1986-12-31 CO     1    3.789E+01   3.937E+01 Teillet&Holben(1994)
                                 -1.773E-04  -8.022E-04
1987-01-01 1987-12-31 CO     1    3.783E+01   3.909E+01 Teillet&Holben(1994)
                                 -1.301E-04  -2.036E-04
1988-01-01 1988-12-31 CO     1    3.778E+01   3.901E+01 Teillet&Holben(1994)
                                 -2.381E-04   1.099E-05
```

3.3 NOAA 11

3.3.1 Responsivity

This sensor was the subject of many post launch calibration studies (see Mitchell *et al.* 1996). The inter-comparison of several methods presented by Mitchell *et al.* showed strong evidence for a significant decline in responsivity over the first year of operation with no discernable trend thereafter. The recommended time series follows the simple linear degradation suggested by Che and Price (1992) over the first 400 days, followed by stable operation at the levels reached by the Che and Price functions thereafter. The latter levels are consistent with the ensemble of results presented by Mitchell *et al.* and are within 0.4% and 4.3% of the results of Vermote and El Saleous (1999) in channels 1 and 2 respectively.

Additional results for this sensor from Rao and Chen (1995) are

$$S_1(t) = 0.1060 \exp(0.33 \times 10^{-4} t)$$
$$S_2(t) = 0.1098 \exp(0.556 \times 10^{-4} t).$$

The continued degradation implied by the exponential function appears to have caused artifacts such as the greening of deserts in the GVI data set (Gutman, private communication). Hence this calibration is not included in the tables.

```
NOAA 11 Responsivity
Launch date:  1988-09-24
Last updated: 1999-03-01
Valid date range
   First      Last    Item Order Channel_1  Channel_2 Source
1981-07-01 1987-10-30 S     0    1.010E-01  0.970E-01 NESDIS(1989)
1987-11-01 1988-09-23 S     0    0.950E-01  0.900E-01 NESDIS(1990)
1988-09-24 1994-08-31 S     0    1.091E-01  1.198E-01 Vermote&El Saleous(1999)
1988-09-24 1989-10-29 S     1    1.030E-01  1.100E-01 Che&Price(1992)
                                 1.433E-05  1.194E-05
1989-10-30 1994-08-31 S     0    1.087E-01  1.149E-01 Mitchell(1999)
```

3.3.2 Space count

```
NOAA 11 Space count
Launch date:  1988-09-24
Last updated: 1999-03-22
Valid date range
   First      Last    Item Order Channel_1  Channel_2 Source
1981-07-01 1988-09-23 CO    0    4.080E+01  4.040E+01 ITT(1992)
1988-09-24 1988-12-31 CO    1    3.998E+01  3.997E+01 Teillet&Holben(1994)
                                 1.220E-04  1.623E-04
1989-01-01 1989-12-31 CO    1    4.000E+01  3.999E+01 Teillet&Holben(1994)
                                 5.815E-05  4.929E-05
1990-01-01 1990-12-31 CO    1    4.002E+01  4.001E+01 Teillet&Holben(1994)
                                -4.236E-05 -1.284E-04
1991-01-01 1991-12-31 CO    1    4.000E+01  3.997E+01 Teillet&Holben(1994)
                                -1.429E-04 -3.062E-04
1992-01-01 1994-08-31 CO    1    3.995E+01  3.985E+01 Teillet&Holben(1994)
                                -2.435E-04 -4.842E-04
```

4 Calibration coefficients for currently operational sensors

4.1 NOAA 12

4.1.1 Responsivity

The pre-launch calibration coefficients issued for the NOAA 12 AVHRR by NESDIS are shown below. The in-flight responsivity measurements were obtained by Loeb (1997) using observations over polar ice during the period June 1994 to December 1995. No significant change was found over this time, hence the mean value over the entire period is reported below.

```
NOAA 12 Responsivity
Launch date:  1991-05-14
Last updated: 1999-03-01
Valid date range
   First        Last    Item Order Channel_1   Channel_2 Source
1990-11-01 1991-05-13 S      0    1.042E-01   1.014E-01 Kidwell(1991)
1994-06-01 1995-12-31 S      0    1.230E-01   1.420E-01 Loeb(1997)
```

4.1.2 Space count

```
NOAA 12 Space count
Launch date:  1991-05-14
Last updated: 1999-03-22
Valid date range
   First        Last    Item Order Channel_1   Channel_2 Source
1990-11-01 1991-05-13 C0     0    4.171E+01   4.031E+01 ITT(NAS5-30887, Task 7B)
1992-07-01 1999-02-28 C0     0    4.030E+01   4.000E+01 Mitchell(1999)
```

4.2 NOAA 14

4.2.1 Responsivity

The pre-launch calibration coefficients issued by NESDIS in February 1995 were found to be anomalous and were revised by Mitchell (1996). NESDIS issued its first in-flight update on July 31, 1995. A calibration trend based on the first year of operation was published by Rao and Chen (1996). This was later found to be in error due to an inadequate period of sampling combined with significant seasonal variation inherent in the method. A revised calibration based on three years of operation was published by Rao and Chen (1999) and is shown below.

The recommended calibration time series follows a polynomial fit to the ocean method of Vermote and El Saleous (1999) covering just over four years' operation. A comparison of the Vermote and El Saleous calibration with that of Rao and Chen (1999) is shown in Figure 1.

For more recent data, a linear extrapolation is recommended. The rate of degradation was derived from a least-squares fit to the data of Vermote and El Saleous over the previous year of operation (1998-01-31 to 1999-01-31), while the constant term follows from the requirement of continuity with the preceeding function when the changeover occurs (1999-01-31).

NOAA 14 Responsivity
Launch date: 1994-12-30
Last updated: 1999-04-22
Valid date range

First	Last	Item	Order	Channel_1	Channel_2	Source
1993-09-01	1994-12-29	S	0	1.081E-01	1.090E-01	NESDIS(1995)
1993-09-01	1994-12-29	S	0	1.059E-01	1.056E-01	Mitchell(1996)
1994-12-30	1997-12-31	S	1	1.110E-01	1.340E-01	Rao&Chen(1999)
				1.350E-05	1.330E-05	
1994-12-30	1999-01-31	S	5	1.111E-01	1.375E-01	Vermote&El Saleous(1999)
				8.548E-05	1.486E-04	
				-2.586E-07	-4.251E-07	
				3.958E-10	5.926E-10	
				-2.723E-13	-3.877E-13	
				6.843E-17	9.496E-17	
1999-01-31	2000-01-31	S	1	1.345E-01	1.624E-01	Extrapolation of V&E(1999)
				7.264E-06	1.844E-06	

4.2.2 Space count

The pre-launch calibration coefficients issued by NESDIS in February 1995 were found to be anomalous and were revised by Mitchell (1996) as shown below. From October 1996, a monthly statistical analysis of the space count has been undertaken at CSIRO following the method described in Section 2.5 above.

NOAA 14 Space count
Launch date: 1994-12-30
Last updated: 1999-03-22
Valid date range

First	Last	Item	Order	Channel_1	Channel_2	Source
1993-09-01	1994-12-29	CO	0	3.575E+01	3.371E+01	NESDIS(1995)
1993-09-01	1994-12-29	CO	0	4.090E+01	4.100E+01	Mitchell(1996)
1994-12-30	1999-03-01	CO	0	4.100E+01	4.100E+01	Mitchell(1999)

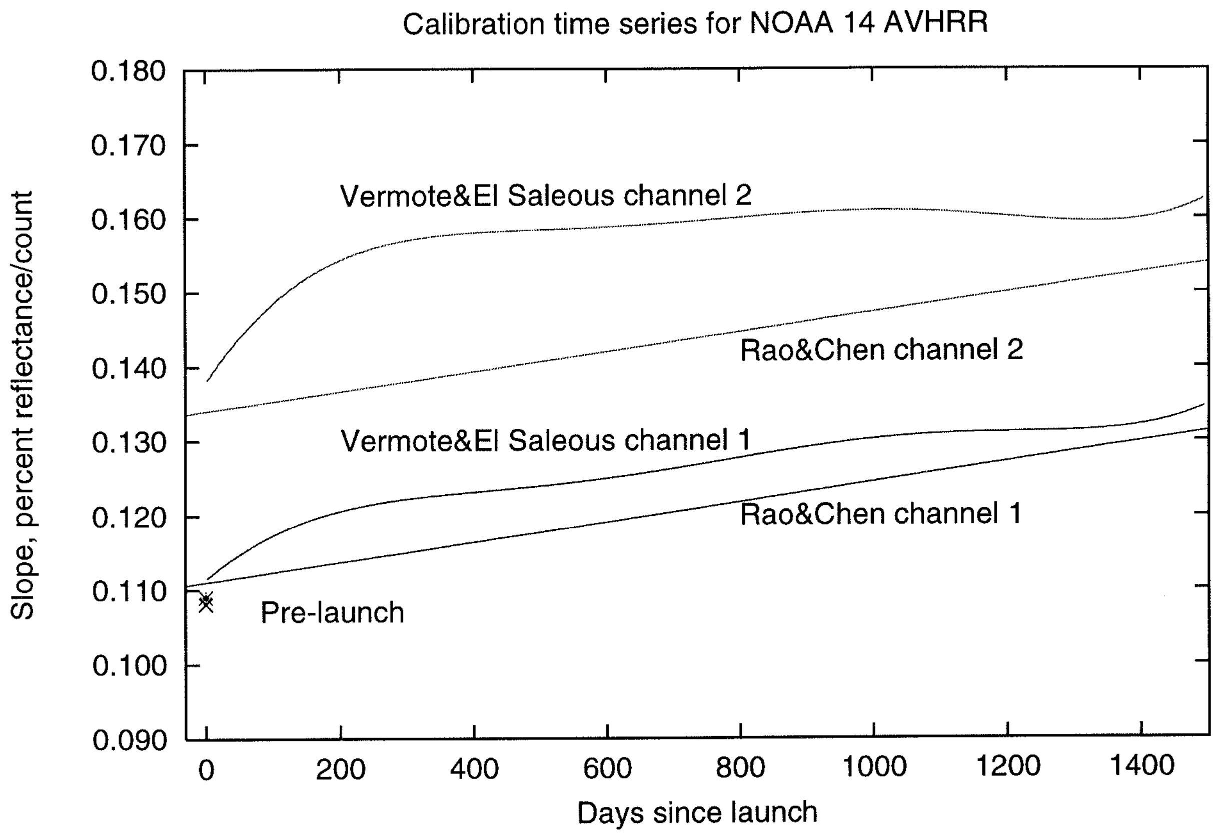

Figure 1: Comparison of responsivity time series for the AVHRR on NOAA 14 from Vermote and El Saleous (1999) and Rao and Chen (1999), together with the pre-launch coefficients released by NESDIS.

4.3 NOAA 15

4.3.1 Responsivity

```
NOAA 15 Responsivity
Launch date:  1998-05-13
Last updated: 1999-04-22
Valid date range
   First        Last    Item Order Channel_1  Channel_2  Channel_3a Source
1998-04-30 1998-05-12 SL    0    5.680E-02  5.960E-02  2.750E-02  NESDIS(1998)
1998-04-30 1998-05-12 SU    0    1.633E-01  1.629E-01  1.846E-01  NESDIS(1998)
```

4.3.2 Space count

The following table lists space count C_0 and transition count C_t for the solar reflectance channels of the NOAA 15 AVHRR.

```
NOAA 15 Space count
Launch date:  1998-05-13
Last updated: 1999-04-22
Valid date range
   First        Last    Item Order Channel_1  Channel_2  Channel_3a Source
1998-04-30 1998-05-12 C0    0    3.850E+01  4.040E+01  3.890E+01  NESDIS(1998)
1998-04-30 1998-05-12 Ct    0    4.960E+02  5.110E+02  4.910E+02  NESDIS(1998)
```

5 Worked example

Suppose the digital counts recorded on January 20 1997 for a given pixel in a NOAA 14 AVHRR image were

$$\begin{aligned} C_1 &= 95 \\ C_2 &= 167. \end{aligned}$$

Reference to the responsivity table for NOAA 14 shows that the calibration data consist of a fifth-order polynomial fit to the determination of slope parameter by Vermote and El Saleous (1999) with reference time at launch date, December 30 1994. The number of days between this date and January 20 1997 is 752. Hence the slopes on this date are

$$\begin{aligned} S_1(1\mathrm{AU}) &= 0.1111 \quad +8.548\times10^{-5}\times752 \quad -2.586\times10^{-7}\times752^2 \\ &\qquad +3.958\times10^{-10}\times752^3 \quad -2.723\times10^{-12}\times752^4 \\ &\qquad +6.843\times10^{-17}\times752^5 \\ &= 0.1268 \end{aligned}$$

$$\begin{aligned} S_2(1\mathrm{AU}) &= 0.1375 \quad +1.486\times10^{-4}\times752 \quad -4.251\times10^{-7}\times752^2 \\ &\qquad +5.926\times10^{-10}\times752^3 \quad -3.877\times10^{-12}\times752^4 \\ &\qquad +9.496\times10^{-17}\times752^5 \\ &= 0.1597. \end{aligned}$$

As discussed above, these slopes are tabulated for a sun-earth distance of 1 AU. The actual sun-earth distance is found by noting that the number of days elapsed between December 31 1974 and January 20 1997 is d_{1975} =8056 and hence, from Equation (2), the mean anomaly is

$$\begin{aligned} g &= (0.9856003\times8056-2.97394) \bmod 360 \\ &= 17.022^\circ \end{aligned}$$

leading to a sun-earth distance from Equation (3) of

$$\begin{aligned} r &= 1.00014-0.01671\cos(17.022)-0.00014\cos(2\times17.022) \\ &= 0.9840 (r^2=0.9683, r^{-2}=1.033). \end{aligned}$$

Hence, from Equation (7)

$$\begin{aligned} S_1 &= 0.1268\times0.9683 \\ &= 0.1228 \end{aligned}$$

and

$$\begin{aligned} S_2 &= 0.1597\times0.9683 \\ &= 0.1546 \end{aligned}$$

Hence the reflectance factors $R_i=(C_i-C_{0i})S_i$ are

$$\begin{aligned} R_1 &= (95-41)\times0.1228 \\ &= 6.63\% \end{aligned}$$

and

$$\begin{aligned} R_2 &= (167-41)\times0.1546 \\ &= 19.5\%. \end{aligned}$$

The corresponding radiances may be found by first calculating the in-band irradiances at this time of year from

$$\overline{F}_i(r) = \overline{F}_i(1\mathrm{AU})r^{-2}.$$

Hence the extraterrestrial in-band irradiances are

$$\begin{aligned}\overline{F}_1 &= 207.1 \times 1.033 \\ &= 213.9\,\mathrm{W\,m^{-2}} \\ \overline{F}_2 &= 251.01 \times 1.033 \\ &= 259.3\,\mathrm{W\,m^{-2}}.\end{aligned}$$

From Equation (1) it follows that

$$\overline{I}_i = \frac{\overline{F}_i(r)R_i}{100\pi}$$

whence

$$\begin{aligned}\overline{I}_i &= \frac{213.9 \times 6.63}{100\pi} \\ &= 4.51\,\mathrm{W\,m^{-2}\,sr^{-1}} \\ \overline{I}_2 &= \frac{259.3 \times 19.5}{100\pi} \\ &= 16.1\,\mathrm{W\,m^{-2}\,sr^{-1}}.\end{aligned}$$

Corresponding mean spectral radiances are

$$\begin{aligned}I_i &= \overline{I}_i/w_i \\ \Rightarrow I_1 &= 4.51/0.129 \\ &= 35.0\,\mathrm{W\,m^{-2}\,\mu m^{-1}\,sr^{-1}} \\ I_2 &= 16.1/0.244 \\ &= 66.0\,\mathrm{W\,m^{-2}\,\mu m^{-1}\,sr^{-1}}.\end{aligned}$$

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