Centre National
d'Etudes Spatiales

S5-NT-0-2880-CN

Edition : 1 Revision : 0
Date : 02/08/2006
Ref: DCT/SI/MO/2006-16141

SPOT ABSOLUTE CALIBRATION : SYNTHESIS

	Fonction et Nom / Date Signature
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Pour Application	

Diffusion	Pour :	
	Action	Info
VOIR LISTE		

CNES	SYSTEME POUR L'OBSERVATION DE LA TERRE	**S5-NT-0-2880-CN** PAGE : 1 EDIT.:1 REV. : 0 DATE : 02/08/2006

BORDEREAU D'INDEXATION

CONFIDENTIALITE : NC

MOTS CLES : SPOT, absolute calibration

TITRE :

SPOT absolute calibration : synthesis

AUTEURS :

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RESUME :

This document provides a synthesis of SPOT1, SPOT2, SPOT4 and SPOT5 absolute calibration and details the different parameters used to deduce a physical quantity from image numerical level.

SITUATION DU DOCUMENT :

Volume :	**Nbre de pages total : 29**	**dont pages liminaires : 7**	**nbre d'annexe : 0**	**LANGUE : E**

DOCUMENT GERE EN CONFIGURATION	**A DATER DU :**	**RESPONSABLE :**

SYSTEME HOTE :

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MODIFICATIONS

EDITION	REV	DATE	MODIFICATIONS	VISA
0	**0**	**03/11/04**	**Document creation**	
1	**0**	**02/08/06**	**Calibration update**	

ETAT DES PAGES DU DOCUMENT

Page	Edition	Révision		Page	Edition	Révision
All	**0**	**0**				

SOMMAIRE

1 OBJECT

This document provides a synthesis of SPOT1, SPOT2, SPOT4 and SPOT5 absolute calibration and details the different parameters used to deduce a physical quantity from image numerical level.

2 DEFINITIONS

After normalization (level 1A or more) and without digital dynamic stretching, the numerical level in the image X_k is proportional to the input radiance L_k:

$$X_k = A_k G_{mk} L_k$$

where:

k is the spectral band,

A_k is the absolute calibration coefficient,

G_{mk} is the analog gain (on-board amplifier), depending on the gain number m

L_k is the normalized radiance:

$$L_k = \frac{\int L(\lambda) S_k(\lambda) d\lambda}{\int S_k(\lambda) d\lambda} \quad (\text{W.m}^{-2}.\text{sr}^{-1}.\mu\text{m}^{-1})$$

where: $L(\lambda)$ is the spectral radiance and $S_k(\lambda)$ the spectral sensitivity of the sensor.

If $E(\lambda)$ is the spectral solar irradiance, the normalized solar irradiance is defined as:

$$E_k = \frac{\int E(\lambda) S_k(\lambda) d\lambda}{\int S_k(\lambda) d\lambda} (\text{W.m}^{-2}.\mu\text{m}^{-1})$$

If $\rho(\lambda)$ is the spectral reflectance, the normalized reflectance is defined as:

$$\rho_k = \frac{\int \rho(\lambda) E(\lambda) S_k(\lambda) d\lambda}{\int E(\lambda) S_k(\lambda) d\lambda}$$

We can then show that the relation

$$L(\lambda) = \frac{\rho(\lambda)}{\pi} E(\lambda) \cos\theta_s$$

becomes:

$$L_k = \frac{\rho_k}{\pi} E_k \cos\theta_s$$

Where θs is the solar zenith angle (angle between the normal and the sun directions).

3 HOW TO GET THESE CALIBRATION PARAMETERS ?

To deal with the previous relations and compute a top of the atmosphere normalized reflectance from a SPOT image, we need the following parameters:

- Ak, the absolute coefficient,
- Gmk, the analog gain,
- θs , the solar zenith angle,
- Ek, the normalized solar irradiance.

3.1 Getting Ak and Gmk

The value of the product Ak.Gmk is given with the auxiliary data as :

- the "PHYSICAL_GAIN" for DIMAP SPOT Scene format,
- the "Absolute Calibration Gain" in the Header record of the Header file, bytes 1765 to 2276.

But it is possible for the user to compute this value as described below.

3.1.1 Determination of Gmk

Gmk is given in tables 1, 2, 3 and 4 as a function of the gain number, the spectral band and the instrument for respectively SPOT1, SPOT2, SPOT4 and SPOT5. The gain number used to address Gmk is provided with the auxiliary data of the image and ranges from 1 to 8 on SPOT1 and SPOT2, from 1 to 6 on SPOT4 and from 1 to 10 on SPOT5. In the DIMAP format (SPOT Scene) it is named 'GAIN_NUMBER'. In the CEOS format it can be found in the Header record of the Leader File, bytes 725 to 740.
Gmk is also provided in the metadata when the format is DIMAP SPOT Scene under the name 'GAIN_ANALOG_VALUE'.
When the image is programmed, the gain number is generally optimized using a statistical estimate of the observed reflectance based on SPOT images previously taken over the same target.

SPOT1		**HRV1**					**HRV2**		
Gain number	**PA**	**B1**	**B2**	**B3**		**PA**	**B1**	**B2**	**B3**
1	0,5921	0,5902	0,5911	0,5895		0,5915	0,5902	0,5920	0,5910
2	0,7712	0,7686	0,7700	0,7672		0,7697	0,7700	0,7705	0,7678
3	1,0000	1,0000	1,0000	1,0000		1,0000	1,0000	1,0000	1,0000
4	1,3025	1,3036	1,3033	1,3026		1,2954	1,3013	1,3078	1,3004
5	1,6908	1,6881	1,6921	1,6979		1,6838	1,6901	1,6969	1,6912
6	2,2038	2,2050	2,2064	2,2136		2,1970	2,1996	2,2185	2,2104
7	2,8701	2,8729	2,8751	2,8821		2,8642	2,8700	2,8902	2,8727
8	3,7286	3,7321	3,7309	3,7473		3,7198	3,7269	3,7501	3,7337

Table 1: SPOT1 analog gains (Gmk)

SPOT2		HRV1				HRV2		
Gain number	PA	B1	B2	B3	PA	B1	B2	B3
1	0,5923	0,5895	0,5904	0,5908	0,5898	0,5892	0,5947	0,5923
2	0,7706	0,7677	0,7707	0,7676	0,7701	0,7672	0,7723	0,7697
3	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000
4	1,3027	1,3002	1,3031	1,2992	1,3016	1,3006	1,3050	1,2988
5	1,6941	1,6888	1,6954	1,6906	1,6898	1,6852	1,7010	1,6917
6	2,2058	2,1964	2,2152	2,2094	2,1999	2,1975	2,2126	2,2115
7	2,8760	2,8646	2,8792	2,8669	2,8659	2,8630	2,8834	2,8727
8	3,7305	3,7182	3,7431	3,7308	3,7153	3,7151	3,7351	3,7345

Table 2: SPOT2 analog gains (Gmk)

SPOT4		HRVIR1					HRVIR2			
Gain number	M	B1	B2	B3	SWIR	PA	B1	B2	B3	SWIR
1	0,6670	0,6670	0,6670	0,6690	0,6670	0,6670	0,6670	0,6670	0,6690	0,6670
2	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000
3	1,5030	1,5030	1,5020	1,4990	1,5050	1,5030	1,5030	1,5020	1,4990	1,5050
4	2,2500	2,2500	2,2470	2,2480	2,2680	2,2500	2,2500	2,2470	2,2480	2,2680
5	3,3850	3,3850	3,3790	3,3680	3,4070	3,3850	3,3850	3,3790	3,3680	3,4070
6	5,0580	5,0580	5,0450	5,0450	5,1280	5,0580	5,0580	5,0450	5,0450	5,1280

Table 3: SPOT4 analog gains (Gmk)

SPOT5		HRG1					HRG2			
Gain number	HMA	B1	B2	B3	SWIR	HMA	B1	B2	B3	SWIR
1	0,6012	0,6006	0,6004	0,6011	0,5910	0,6000	0,6010	0,6010	0,6010	0,5930
2	0,7994	0,7989	0,7990	0,7987	0,7688	0,7990	0,7990	0,7990	0,7990	0,7690
3	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000
4	1,2007	1,2005	1,2005	1,2008	1,2999	1,2000	1,2000	1,2010	1,2000	1,2990
5	1,5981	1,5948	1,5964	1,5969	1,6902	1,5950	1,5940	1,5950	1,5950	1,6890
6	2,2009	2,1990	2,2001	2,2019	2,2000	2,1960	2,1980	2,1960	2,1980	2,1950
7	2,8032	2,8029	2,8039	2,8047	2,8610	2,7960	2,8040	2,7980	2,7980	2,8540
8	3,7986	3,8005	3,8018	3,8044	3,7230	3,7880	3,8050	3,7910	3,7910	3,7070
9	4,8013	4,7998	4,7933	4,8044	4,8436	4,7840	4,7950	4,7850	4,7880	4,8160
10	6,2087	6,2116	6,2014	6,2193		6,1860	6,2090	6,1960	6,2050	

Table 4: SPOT5 analog gains (Gmk)

3.1.2 Determination of Ak

Until last year SPOT1, SPOT2, SPOT4 and SPOT5 calibration was mainly based on vicarious calibration over test sites; calibration over natural targets like oceans for Rayleigh scattering and cross calibration with regards to wide field of view sensors like VEGETATION or POLDER over stable deserts were also performed. The calibration temporal evolution was

monitored with the on-board lamp for SPOT1 to 4 and with deserts for SPOT5 which do not fly any calibration unit.
The effort that was made to spectrally and directionnaly characterize 20 deserts over North Africa and Middle East allowed us to get a better knowledge of the cameras sensitivity evolution and showed that the calibration units were loosing sensitivity. This progress has led us to update the overall calibration of SPOT satellites to both correct this evolution and improve cross-SPOT calibration.

For multispectral bands, the new SPOT calibration scheme is the following:

- SPOT4 HRVIR1 is used as a reference. Bands 1 and 2 are calibrated over the Rayleigh scattering . Bands 3 and 4 calibration is deduced from cross-calibration with regard to VEGETATION 2 over deserts. Vicarious calibrations over test sites are performed for all bands. The calibration temporal evolution is monitored with cross-calibration over deserts using POLDER as a reference for bands 1, 2 and 3 and VEGETATION 2 for band 4.
- SPOT1 HRV1, SPOT2 HRV2 and SPOT5 HRG1, named as reference cameras for each spacecraft, are cross-calibrated with regard to SPOT4 HRVIR1 over deserts. Vicarious calibrations over test sites are performed for validation. Moreover, calibration over the Rayleigh scattering for bands 1 and 2, and cross-calibration over deserts using POLDER, VEGETATION 1 and 2 as references are performed for SPOT5 HRG1 calibration validation.
- the second camera of the spacecraft (SPOT1 HRV2, SPOT2 HRV1, SPOT4 HRVIR2 and SPOT5 HRG2) is cross-calibrated with regard to the reference camera using simultaneous viewing over different landscapes.

For Panchromatic bands the reference camera on each spacecraft becomes HRV2 for SPOT1, HRV1 for SPOT2 and remains HRG1 for SPOT5. SPOT1 HRV2, SPOT2 HRV1 and SPOT5 HRG1 panchromatic bands are cross-calibrated over deserts with regard to respectively SPOT4 HRVIR1, SPOT2 HRV2 and SPOT5 HRG1 multi-spectral bands. The second camera on the spacecraft (SPOT1 HRV1, SPOT2 HRV2 and SPOT5 HRG2) is cross-calibrated with regard to the reference camera using simultaneous viewing over different landscapes.

<u>The new calibration coefficient is provided:</u>

- **for the reference camera** of each spacecraft (SPOT1 HRV1, SPOT2 HRV2, SPOT4 HRVIR1, SPOT5 HRG1 for XS bands and SPOT1 HRV2, SPOT2 HRV1, SPOT5 HRG2 for PA bands), as a ‘log-linear’ model, with 3 parameters a, b and c, which is fitted to the in-flight absolute measurements:

$$A_{k,r}(t) = a + b.t + c.\ln(t)$$

where k is the spectral band, r the reference camera, t the number of days since the launch and ‘ln’ the neperien logarithm.

This model gives a good description of the camera sensitivity evolution: the logarithm fits quite well the spectral filter gazing under vacuum conditions at the beginning of life while the following optics yellowing induces a quasi-linear sensitivity evolution.

- **for the cross-calibrated camera** (SPOT1 HRV2, SPOT2 HRV1, SPOT4 HRVIR2, SPOT5 HRG2 for XS bands and SPOT1 HRV1, SPOT2 HRV2, SPOT5 HRG1 for PA bands), as a function of the calibration of the reference camera using a 'log-linear' model, with 3 parameters α, β and γ, which is fitted to the in-flight cross-calibration measurements:

$$A_{k,c}(t) = (\alpha + \beta.t + \gamma.\ln(t)).\ A_{k,r}(t)$$

t is the number of days since the launch, 'ln' the neperien logarithm and $A_{k,r}(t)$ the calibration coefficient of the reference camera.

These parameters are provided in tables 6 to 12 for each satellite, instrument and spectral band. Calibration coefficients are also estimated for different dates from the launch to the end of 2005 in tables 13 to 17.
It is important to note that the 'log-linear' model is not valid before November 1988 for SPOT1 and November 1990 because of the lack of data over deserts. So for these periods (launch to October 1988 for SPOT1 and to October 1990 for SPOT2) the calibration temporal evolution is provided by the on-board lamp corrected from a linear transmission variation of the calibration unit; this correction is estimated by fitting lamp measurement to vicarious calibrations over test sites.

	SPOT1	SPOT2	SPOT4	SPOT5
Launch day (t=0)	22/02/1986	22/01/1990	24/03/1998	04/05/2002

Table 5: Launch day for each SPOT satellite, giving the reference day for the absolute calibration temporal model (t=0).

SPOT1		HRV1					HRV2	
	XS1	XS2	XS3			XS1	XS2	XS3
a	4,6985E-01	4,6398E-01	8,4374E-01		α	1,0203E+00	1,1379E+00	1,0316E+00
b	-1,9376E-05	-2,2773E-06	5,5496E-06		β	-7,8041E-06	-9,8412E-07	4,1492E-06
c	4,9782E-03	-1,5915E-02	-4,1250E-02		γ	0	0	0

Table 6: SPOT1 XS absolute calibration parameters.

SPOT1	HRV1			HRV2
	PA			PA
α	1,0076E+00		a	7,8456E-01
β	5,5216E-06		b	-1,0542E-05
γ	0		c	-2,3180E-02

Table 7: SPOT1 PA absolute calibration parameters

SPOT2		HRV1					HRV2	
	XS1	XS2	XS3			XS1	XS2	XS3
α	9,0099E-01	9,9106E-01	1,0213E+00		a	8,7689E-01	4,9902E-01	7,4787E-01
β	-3,7176E-06	-1,9416E-06	-6,2789E-07		b	-3,8458E-06	-3,4033E-06	-1,4562E-06
γ	-1,3152E-03	2,0101E-03	-1,7392E-03		c	-4,8162E-02	-1,3350E-02	-3,8287E-04

Table 8: SPOT2 absolute calibration parameters

SPOT2	HRV1			HRV2
	PA			PA
a	5,5748E-01		α	1,2217
b	-5,9068E-06		β	1,0819E-05
c	-8,5451E-03		γ	-3,3122E-03

Table 9: SPOT2 PA absolute calibration parameters

SPOT4		HRVIR1					HRV2		
	B1	B2	B3	SWIR		B1	B2	B3	SWIR
a	9,1096E-01	1,0452E+00	1,0473E+00	5,5657E+00	α	9,6695E-01	9,9804E-01	1,0563E+00	9,7189E-01
b	-1,0737E-05	-3,0804E-06	1,0619E-05	-5,9774E-05	β	-7,7186E-06	-1,6459E-06	-2,4291E-06	3,7712E-06
c	-2,8543E-02	-2,4727E-02	-2,4641E-02	9,7841E-02	γ	-2,2531E-03	-3,0448E-03	-2,0772E-03	-1,1467E-02

Table 10: SPOT4 absolute calibration parameters

SPOT5		HRG1					HRG2		
	B1	B2	B3	SWIR		B1	B2	B3	SWIR
a	1,0164E+00	1,1711E+00	1,3085E+00	6,2769E+00	α	9,7052E-01	1,0338E+00	9,4517E-01	9,8859E-01
b	7,1907E-06	2,0471E-05	3,6477E-05	7,3674E-05	β	1,2320E-07	-1,9036E-05	-5,9551E-06	-8,6087E-07
c	-2,7856E-02	-2,7398E-02	-3,6378E-02	1,0733E-02	γ	-7,4785E-03	-3,7726E-04	7,7216E-03	1,9956E-03

Table 11: SPOT5 J absolute calibration parameters

SPOT5	HRG1			HRG2
	HMA			HMA
a	1,0189E+00		α	1,0417E+00
b	4,4700E-06		β	1,8776E-05
c	-1,9176E-02		γ	-8,2108E-03

Table 12: SPOT5 HMA absolute calibration parameters

SPOT1		HRV1					HRV2			
t	day	XS1	XS2	XS3	PA		XS1	XS2	XS3	PA
1	23/02/1986	0,555	0,436	0,653	0,656		0,566	0,496	0,673	0,651
10	04/03/1986	0,553	0,434	0,650	0,655		0,564	0,493	0,670	0,650
20	14/03/1986	0,551	0,431	0,647	0,654		0,563	0,490	0,667	0,649
30	24/03/1986	0,550	0,428	0,644	0,653		0,561	0,487	0,664	0,647
40	03/04/1986	0,548	0,425	0,640	0,651		0,559	0,483	0,661	0,646
50	13/04/1986	0,546	0,422	0,637	0,650		0,557	0,480	0,658	0,645
60	23/04/1986	0,545	0,419	0,634	0,649		0,556	0,476	0,654	0,644
70	03/05/1986	0,543	0,416	0,631	0,648		0,554	0,473	0,651	0,643
80	13/05/1986	0,541	0,413	0,628	0,647		0,552	0,470	0,648	0,642
90	23/05/1986	0,540	0,410	0,625	0,646		0,550	0,466	0,645	0,641
100	02/06/1986	0,538	0,407	0,622	0,646		0,549	0,463	0,642	0,641
150	22/07/1986	0,533	0,399	0,613	0,643		0,543	0,453	0,633	0,638
200	10/09/1986	0,529	0,394	0,607	0,641		0,539	0,448	0,627	0,636
300	19/12/1986	0,520	0,384	0,597	0,637		0,529	0,437	0,616	0,631
400	29/03/1987	0,513	0,376	0,589	0,634		0,522	0,428	0,609	0,628
500	07/07/1987	0,507	0,371	0,583	0,632		0,515	0,422	0,603	0,625
600	15/10/1987	0,502	0,366	0,578	0,630		0,510	0,416	0,598	0,623
700	23/01/1988	0,497	0,361	0,574	0,628		0,504	0,411	0,594	0,620
800	02/05/1988	0,493	0,358	0,570	0,626		0,499	0,407	0,590	0,618
900	10/08/1988	0,489	0,355	0,567	0,623		0,495	0,403	0,587	0,615
1000	18/11/1988	0,486	0,352	0,564	0,620		0,492	0,400	0,585	0,612
1200	06/06/1989	0,482	0,348	0,558	0,616		0,487	0,396	0,578	0,608
1410	02/01/1990	0,479	0,345	0,552	0,611		0,483	0,393	0,573	0,602
1500	02/04/1990	0,477	0,344	0,550	0,609		0,481	0,391	0,571	0,599
2000	15/08/1991	0,469	0,338	0,541	0,598		0,471	0,384	0,563	0,587
2500	27/12/1992	0,460	0,334	0,535	0,589		0,461	0,379	0,557	0,577
3000	11/05/1994	0,452	0,330	0,530	0,581		0,450	0,374	0,554	0,567
3500	23/09/1995	0,443	0,326	0,527	0,574		0,440	0,370	0,551	0,559
4000	04/02/1997	0,434	0,323	0,524	0,566		0,429	0,366	0,549	0,550
4500	19/06/1998	0,425	0,320	0,522	0,560		0,418	0,363	0,548	0,542
5000	01/11/1999	0,415	0,317	0,520	0,553		0,408	0,359	0,547	0,534
5500	15/03/2001	0,406	0,314	0,519	0,547		0,397	0,356	0,547	0,527
6000	28/07/2002	0,397	0,312	0,518	0,541		0,386	0,353	0,547	0,520
6400	01/09/2003	0,389	0,310	0,518	0,536		0,378	0,351	0,548	0,514

Table 13: calibration coefficient (Ak) for SPOT1 ($W^{-1}.m^2.sr.\mu m$)

SPOT2		HRV1					HRV2			
t	day	XS1	XS2	XS3	PA		XS1	XS2	XS3	PA
1	23/01/1990	0,610	0,476	0,836	0,538		0,677	0,480	0,818	0,657
10	01/02/1990	0,598	0,460	0,802	0,527		0,666	0,462	0,789	0,639
20	11/02/1990	0,587	0,452	0,792	0,522		0,654	0,453	0,780	0,633
30	21/02/1990	0,576	0,446	0,785	0,519		0,643	0,447	0,773	0,628
40	03/03/1990	0,569	0,442	0,781	0,517		0,635	0,443	0,769	0,626
50	13/03/1990	0,565	0,440	0,778	0,517		0,630	0,441	0,767	0,625
60	23/03/1990	0,560	0,438	0,775	0,516		0,626	0,439	0,764	0,623
70	02/04/1990	0,558	0,437	0,773	0,515		0,623	0,437	0,763	0,623
80	12/04/1990	0,556	0,436	0,772	0,515		0,621	0,436	0,762	0,622
90	22/04/1990	0,554	0,435	0,771	0,514		0,619	0,435	0,760	0,621
100	02/05/1990	0,552	0,434	0,769	0,514		0,617	0,434	0,759	0,620
150	21/06/1990	0,545	0,429	0,763	0,512		0,610	0,429	0,753	0,618
200	10/08/1990	0,542	0,426	0,758	0,511		0,607	0,426	0,749	0,616
300	18/11/1990	0,531	0,423	0,754	0,507		0,595	0,422	0,745	0,611
400	26/02/1991	0,522	0,419	0,752	0,504		0,586	0,418	0,744	0,608
500	06/06/1991	0,513	0,415	0,752	0,501		0,576	0,414	0,745	0,605
600	14/09/1991	0,504	0,413	0,752	0,499		0,566	0,412	0,745	0,603
700	23/12/1991	0,497	0,410	0,751	0,497		0,559	0,409	0,744	0,601
800	01/04/1992	0,491	0,408	0,751	0,496		0,552	0,407	0,744	0,599
900	10/07/1992	0,485	0,406	0,751	0,494		0,546	0,405	0,744	0,597
1000	18/10/1992	0,480	0,405	0,750	0,493		0,540	0,403	0,744	0,596
1500	02/03/1994	0,460	0,397	0,749	0,486		0,519	0,396	0,743	0,590
2000	15/07/1995	0,445	0,392	0,747	0,481		0,503	0,391	0,742	0,586
2500	26/11/1996	0,432	0,387	0,746	0,476		0,490	0,386	0,741	0,582
3000	10/04/1998	0,422	0,382	0,745	0,471		0,480	0,382	0,740	0,579
3500	23/08/1999	0,413	0,378	0,743	0,467		0,470	0,378	0,740	0,576
4000	04/01/2001	0,404	0,375	0,742	0,463		0,462	0,375	0,739	0,573
4500	19/05/2002	0,397	0,371	0,741	0,459		0,454	0,371	0,738	0,570
5000	01/10/2003	0,390	0,368	0,740	0,455		0,447	0,368	0,737	0,568
5400	04/11/2004	0,385	0,365	0,739	0,452		0,442	0,366	0,737	0,566
5600	23/05/2005	0,382	0,364	0,738	0,451		0,440	0,365	0,736	0,565
5800	09/12/2005	0,380	0,363	0,738	0,449		0,437	0,364	0,736	0,564

Table 14: calibration coefficient (Ak) for SPOT2 ($W^{-1}.m^2.sr.\mu m$)

SPOT4			HRVIR1					HRVIR2		
t	days	B1	B2	B3	SWIR		B1	B2	B3	SWIR
1	25/03/1998	0,911	1,045	1,047	5,566		0,881	1,043	1,106	5,409
10	03/04/1998	0,845	0,988	0,991	5,790		0,813	0,979	1,042	5,475
20	13/04/1998	0,825	0,971	0,974	5,858		0,792	0,960	1,022	5,492
30	23/04/1998	0,814	0,961	0,964	5,897		0,780	0,949	1,011	5,502
40	03/05/1998	0,805	0,954	0,957	5,924		0,772	0,941	1,003	5,508
50	13/05/1998	0,799	0,948	0,951	5,945		0,765	0,935	0,997	5,513
60	23/05/1998	0,793	0,944	0,947	5,963		0,760	0,930	0,992	5,517
70	02/06/1998	0,789	0,940	0,943	5,977		0,755	0,926	0,988	5,520
80	12/06/1998	0,785	0,937	0,940	5,990		0,751	0,922	0,984	5,522
90	22/06/1998	0,782	0,934	0,937	6,001		0,747	0,919	0,981	5,524
100	02/07/1998	0,778	0,931	0,935	6,010		0,744	0,916	0,978	5,526
150	21/08/1998	0,766	0,921	0,925	6,047		0,731	0,905	0,968	5,533
200	10/10/1998	0,758	0,914	0,919	6,072		0,722	0,897	0,960	5,537
300	18/01/1999	0,745	0,903	0,910	6,106		0,709	0,885	0,950	5,542
400	28/04/1999	0,736	0,896	0,904	6,128		0,699	0,877	0,943	5,544
500	06/08/1999	0,728	0,890	0,899	6,144		0,691	0,871	0,937	5,545
600	14/11/1999	0,722	0,885	0,896	6,156		0,684	0,865	0,933	5,545
700	22/02/2000	0,716	0,881	0,893	6,165		0,678	0,861	0,930	5,545
800	01/06/2000	0,712	0,877	0,891	6,172		0,673	0,857	0,927	5,544
900	09/09/2000	0,707	0,874	0,889	6,177		0,668	0,853	0,925	5,543
1000	18/12/2000	0,703	0,871	0,888	6,182		0,663	0,850	0,923	5,542
1500	02/05/2002	0,686	0,860	0,883	6,192		0,644	0,837	0,916	5,533
2000	14/09/2003	0,673	0,851	0,881	6,190		0,628	0,827	0,913	5,523
2200	01/04/2004	0,668	0,848	0,881	6,187		0,623	0,824	0,912	5,519
2400	18/10/2004	0,663	0,845	0,881	6,184		0,617	0,820	0,911	5,514
2600	06/05/2005	0,659	0,843	0,881	6,180		0,612	0,817	0,911	5,509
2800	22/11/2005	0,654	0,840	0,881	6,175		0,607	0,815	0,911	5,505

Table 15 : calibration coefficient (Ak) for SPOT4 ($W^{-1}.m^2.sr.\mu m$)

SPOT5			HRG1					HRG2		
t	days	B1	B2	B3	SWIR		B1	B2	B3	SWIR
1	05/05/2002	1,016	1,171	1,309	6,277		0,986	1,211	1,237	6,205
10	14/05/2002	0,952	1,108	1,225	6,302		0,908	1,144	1,180	6,259
20	24/05/2002	0,933	1,089	1,200	6,310		0,885	1,125	1,162	6,276
30	03/06/2002	0,922	1,078	1,186	6,316		0,871	1,113	1,152	6,286
40	13/06/2002	0,914	1,071	1,176	6,319		0,862	1,105	1,144	6,294
50	23/06/2002	0,908	1,065	1,168	6,323		0,854	1,098	1,139	6,299
60	03/07/2002	0,903	1,060	1,162	6,325		0,848	1,093	1,134	6,304
70	13/07/2002	0,899	1,056	1,156	6,328		0,843	1,089	1,131	6,309
80	23/07/2002	0,895	1,053	1,152	6,330		0,839	1,085	1,127	6,312
90	02/08/2002	0,892	1,050	1,148	6,332		0,835	1,082	1,124	6,316
100	12/08/2002	0,889	1,047	1,145	6,334		0,832	1,079	1,122	6,319
150	01/10/2002	0,878	1,037	1,132	6,342		0,819	1,067	1,112	6,332
200	20/11/2002	0,870	1,030	1,123	6,348		0,810	1,059	1,106	6,342
300	28/02/2003	0,860	1,021	1,112	6,360		0,798	1,047	1,098	6,358
400	08/06/2003	0,852	1,015	1,105	6,371		0,789	1,039	1,093	6,372
500	16/09/2003	0,847	1,011	1,101	6,380		0,783	1,033	1,090	6,384
600	25/12/2003	0,842	1,008	1,098	6,390		0,777	1,028	1,088	6,395
700	03/04/2004	0,839	1,006	1,096	6,399		0,773	1,024	1,086	6,406
800	12/07/2004	0,836	1,004	1,094	6,408		0,770	1,020	1,086	6,415
900	20/10/2004	0,833	1,003	1,094	6,416		0,766	1,017	1,085	6,425
1000	28/01/2005	0,831	1,002	1,094	6,425		0,764	1,014	1,086	6,434
1100	08/05/2005	0,829	1,002	1,094	6,433		0,761	1,012	1,086	6,443
1200	16/08/2005	0,827	1,001	1,094	6,441		0,759	1,010	1,086	6,452
1300	24/11/2005	0,826	1,001	1,095	6,450		0,757	1,008	1,087	6,461

Table 16: calibration coefficient (Ak) for SPOT5 J ($W^{-1}.m^2.sr.\mu m$)

SPOT5		HRG1		HRG2
t	days	HMA		HMA
1	05/05/2002	1,019		1,061
10	14/05/2002	0,975		0,997
20	24/05/2002	0,962		0,978
30	03/06/2002	0,954		0,967
40	13/06/2002	0,948		0,960
50	23/06/2002	0,944		0,954
60	03/07/2002	0,941		0,949
70	13/07/2002	0,938		0,945
80	23/07/2002	0,935		0,942
90	02/08/2002	0,933		0,939
100	12/08/2002	0,931		0,936
150	01/10/2002	0,923		0,927
200	20/11/2002	0,918		0,920
300	28/02/2003	0,911		0,911
400	08/06/2003	0,906		0,906
500	16/09/2003	0,902		0,902
600	25/12/2003	0,899		0,899
700	03/04/2004	0,896		0,897
800	12/07/2004	0,894		0,896
900	20/10/2004	0,892		0,895
1000	28/01/2005	0,891		0,894

1100	08/05/2005	0,890		0,894
1200	16/08/2005	0,888		0,894
1300	24/11/2005	0,887		0,894

Table 17: calibration coefficient (Ak) for SPOT5 HMA ($W^{-1}.m^2.sr.\mu m$)

3.2 Determination of θs

The sun elevation Els is provided with the auxillary data (key word for the DIMAP format: 'SUN_ELEVATION'). The sun zenith angle is deduced as: θs=90 – Els

3.3 Estimation of Ek

The values of the normalized solar irradiance (table 18) have been computed using WMO (World Meteorogical Organization) spectral solar irradiance.

Satellite	Instrument	PA	B1	B2	B3	SWIR
SPOT1	HRV1	1681,5	1861,7	1633,1	1089,4	
SPOT1	HRV2	1680,7	1853,9	1586	1043,5	
SPOT2	HRV1	1712,5	1873,3	1634	1082	
SPOT2	HRV2	1675,5	1871,1	1626,2	1088,1	
SPOT4	HRVIR1		1842,9	1570,2	1052,1	235,84
SPOT4	HRVIR2		1850,9	1589	1054,8	241,93
SPOT5	HRG1	1764,2	1859,8	1575,3	1043,9	238,87
SPOT5	HRG2	1775	1859,8	1577,6	1048,2	237,78

Table 18: Normalized solar irradiance

These values have to be corrected of the earth-sun distance. The values given in table 18 are computed for a mean earth-sun distance and have to be multiplied by u(t) defined as:

$$u(t) = \frac{1}{(1 - e \cdot \cos(n(t - to)))^2}$$

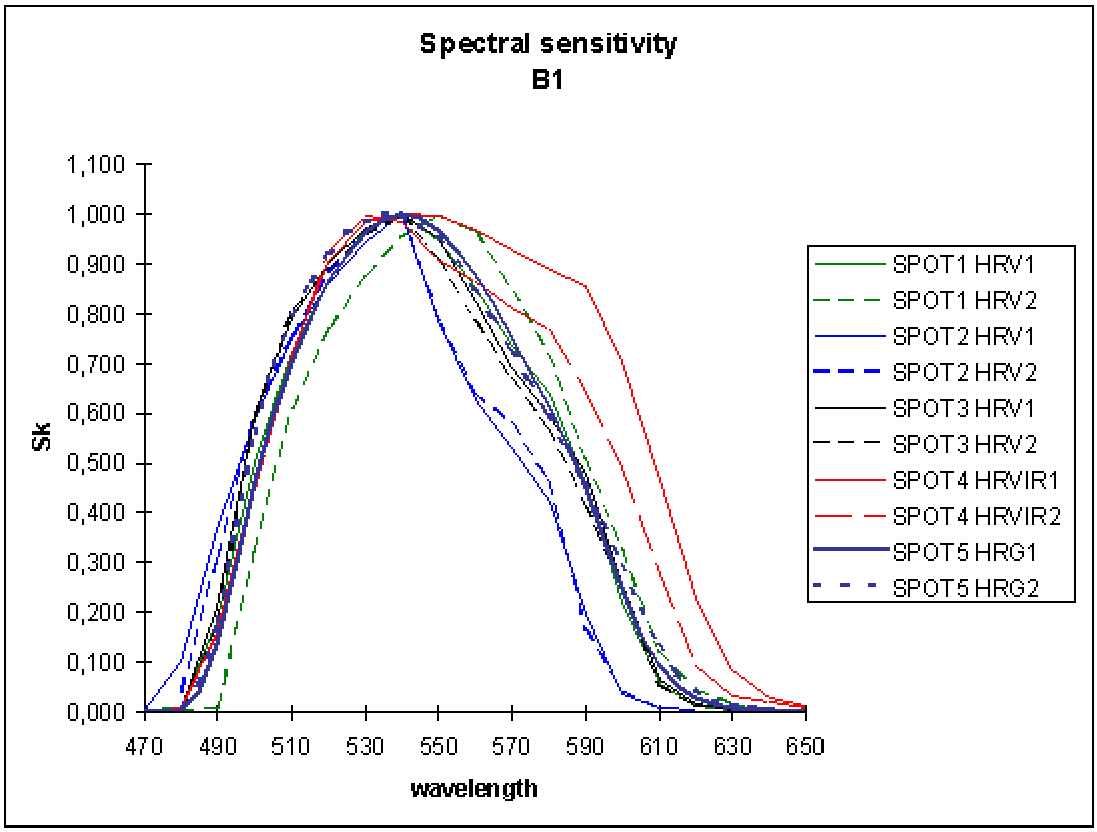
where:

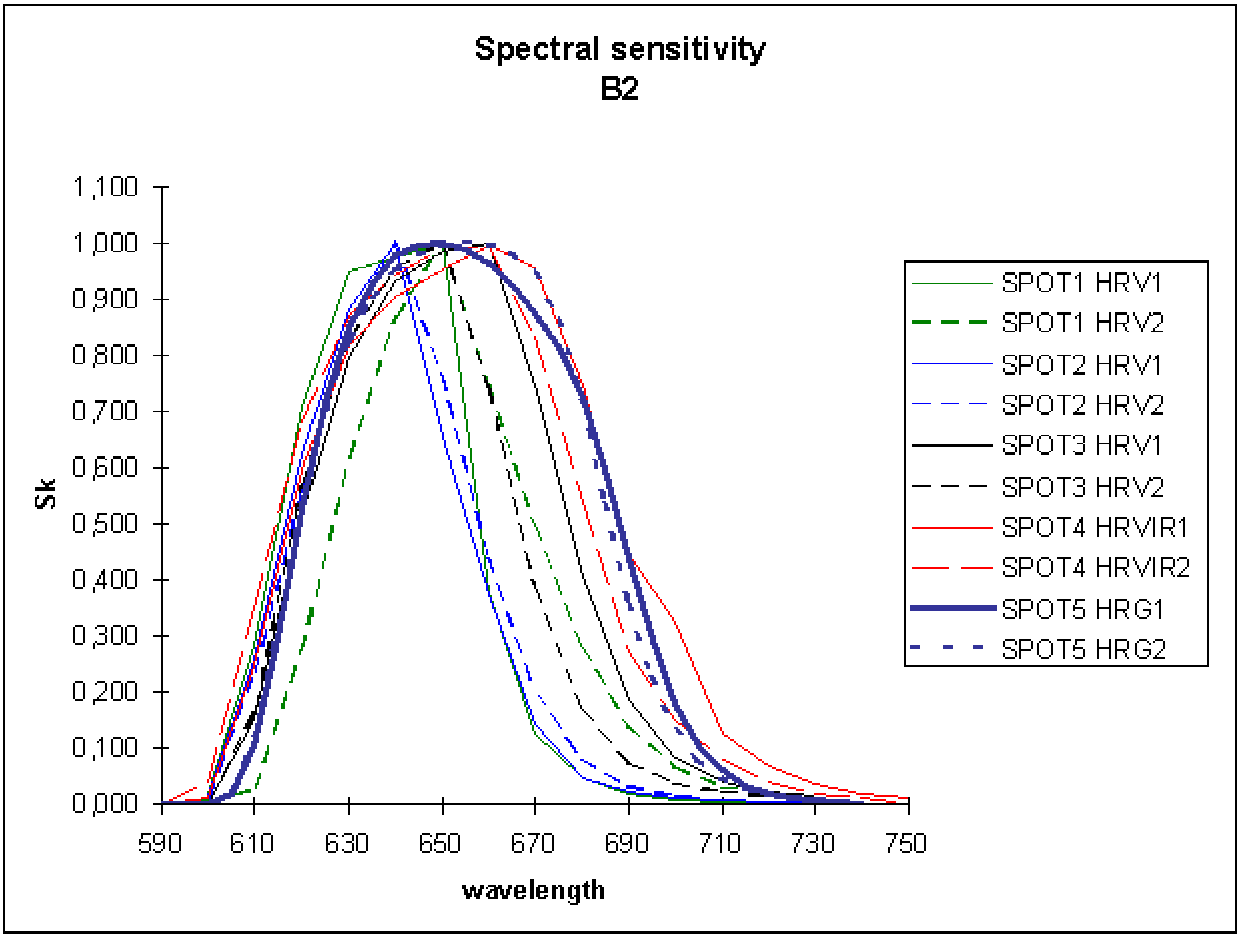
- t is the julian day for the processed image (reference day=01/01/1950)
- to=2
- e=orbit excentricity (0.01673)
- n= mean rotation angle (0.0172 rad/day)

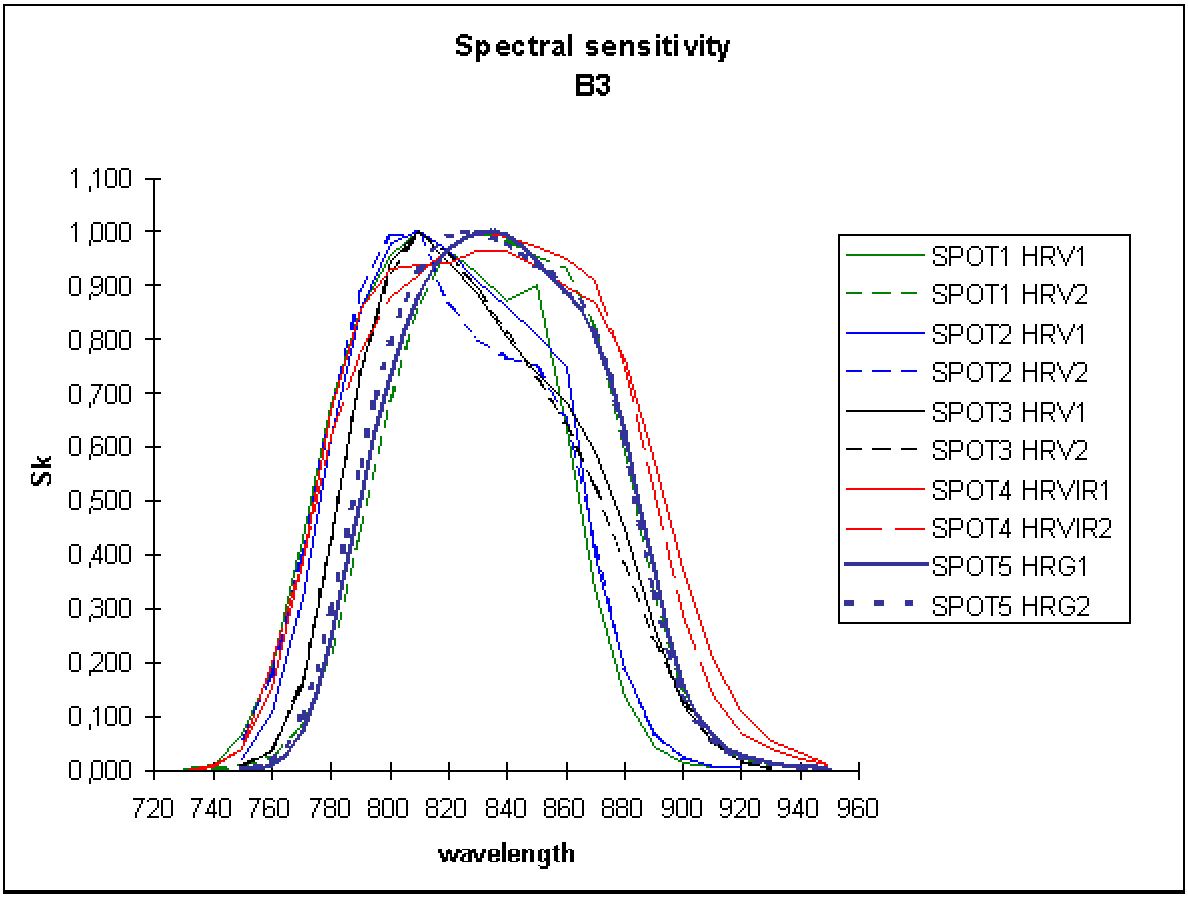
Normalized solar irradiances and SPOT spectral bands can be found at
`http://www.spotimage.fr/automne_modules_files/standard/public/p555_fileLINKEDFILE_spectral-sens.xls`

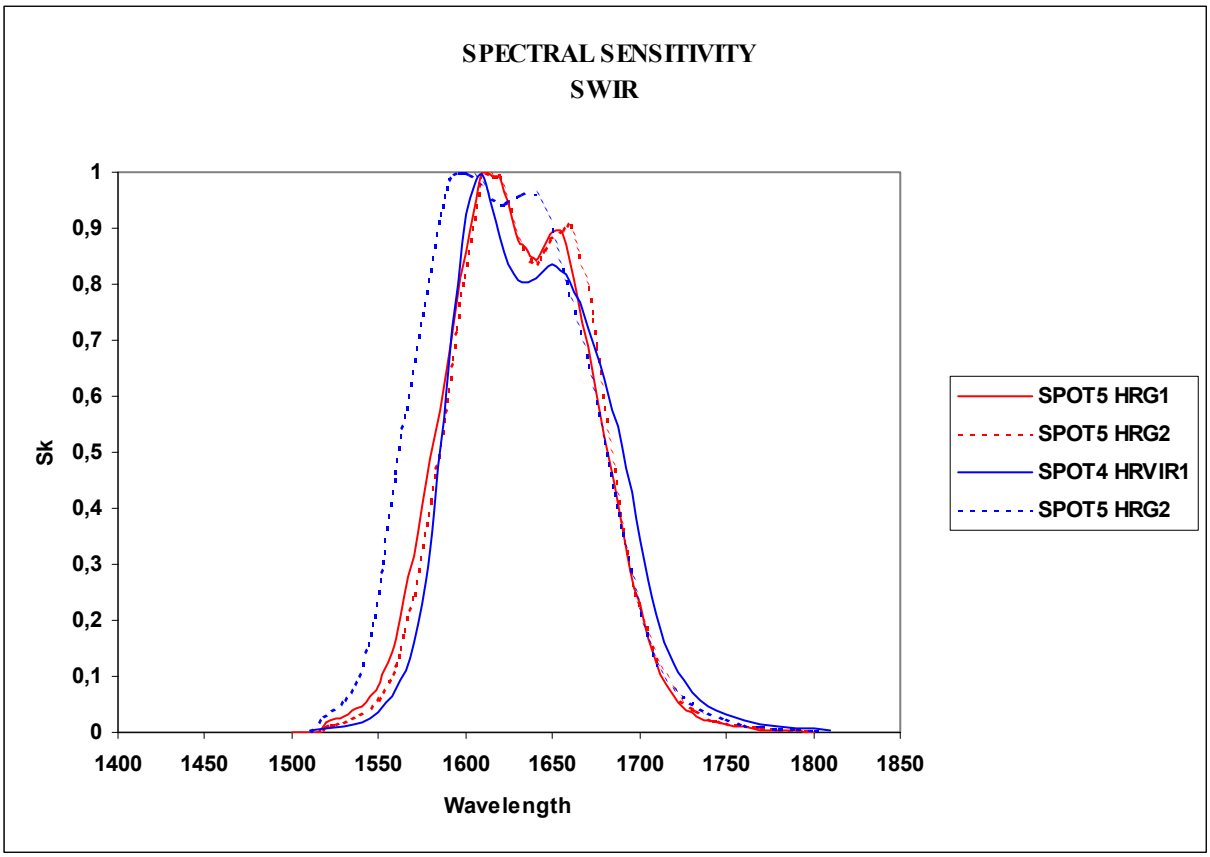
3.4 Description of SPOT spectral bands

The spectral responses $S_k(\lambda)$ of the different instruments on SPOT1, SPOT2, SPOT4 and SPOT5 were measured before the launch under vacuum conditions and are described in tables 19 to 22. These spectral responses are also provided with the auxiliary data of the image: key word 'SPECTRAL_SENSITIVITY_VALUE' for DIMAP format.




Spectral sensitivity
B2
Sk
1,100
1,000
0,900
0,800
0,700
0,600
0,500
0,400
0,300
0,200
0,100
0,000
590
610
630
650
670
690
710
730
750
wavelength
SPOT1 HRV1
SPOT1 HRV2
SPOT2 HRV1
SPOT2 HRV2
SPOT3 HRV1
SPOT3 HRV2
SPOT4 HRVIR1
SPOT4 HRVIR2
SPOT5 HRG1
SPOT5 HRG2


Spectral sensitivity
B3
Sk
1,100
1,000
0,900
0,800
0,700
0,600
0,500
0,400
0,300
0,200
0,100
0,000
720 740 760 780 800 820 840 860 880 900 920 940 960
wavelength
SPOT1 HRV1
SPOT1 HRV2
SPOT2 HRV1
SPOT2 HRV2
SPOT3 HRV1
SPOT3 HRV2
SPOT4 HRVIR1
SPOT4 HRVIR2
SPOT5 HRG1
SPOT5 HRG2


SPECTRAL SENSITIVITY
SWIR
Sk
1
0,9
0,8
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0
1400
1450
1500
1550
1600
1650
1700
1750
1800
1850
Wavelength
SPOT5 HRG1
SPOT5 HRG2
SPOT4 HRVIR1
SPOT5 HRG2

SPOT1	HRV1					HRV2			
LAMBDA									
(nm)	PA	B1	B2	B3		PA	B1	B2	B3
470	0,000	0,001				0,001	0,001		
480	0,005	0,006				0,002	0,003		
490	0,114	0,179				0,049	0,007		
500	0,347	0,502				0,212	0,319		
510	0,458	0,724				0,351	0,610		
520	0,526	0,863				0,437	0,770		
530	0,637	0,971				0,551	0,876		
540	0,719	1,000				0,644	0,955		
550	0,734	0,950				0,670	1,000		
560	0,746	0,852				0,691	0,966		
570	0,800	0,734				0,740	0,847		
580	0,865	0,640				0,792	0,718		
590	0,912	0,458				0,835	0,510	0,004	
600	0,919	0,220	0,019			0,866	0,325	0,006	
610	0,941	0,055	0,281			0,879	0,120	0,028	
620	0,932	0,010	0,705			0,895	0,045	0,273	
630	0,953	0,004	0,950			0,925	0,016	0,618	
640	0,971	0,002	0,973			0,971	0,001	0,867	
650	1,000		1,000			1,000		1,000	
660	0,959		0,378			0,972		0,746	
670	0,903		0,127			0,903		0,494	
680	0,803		0,046			0,812		0,280	
690	0,699		0,020			0,742		0,141	
700	0,631		0,009			0,599		0,066	
710	0,601		0,005			0,438		0,032	
720	0,411		0,003			0,243		0,017	
730	0,215			0,001		0,105		0,010	
740	0,085			0,010		0,043			0,002
750	0,033			0,065		0,018			0,006
760	0,014			0,186		0,008			0,024
770	0,006			0,430		0,004			0,080
780	0,004			0,677		0,002			0,216
790	0,002			0,858		0,001			0,441
800				0,956					0,684
810				1,000					0,867
820				0,966					0,967
830				0,925					1,000
840				0,870					0,987
850				0,901					0,956
860				0,634					0,932
870				0,338					0,823
880				0,136					0,597
890				0,044					0,331
900				0,012					0,147
910				0,007					0,059
920				0,006					0,022
930									0,008

Table 19 : SPOT1 Spectral sensitivities

SPOT2	HRV1					HRV2			
LAMBDA									
(nm)	PA	B1	B2	B3		PA	B1	B2	B3
470	0,002	0,002				0,001			
480	0,02	0,098				0,03	0,038		
490	0,21	0,364				0,199	0,31		
500	0,381	0,586				0,396	0,594		
510	0,489	0,75				0,487	0,756		
520	0,574	0,861				0,541	0,885		
530	0,637	0,946				0,606	0,962		
540	0,687	1				0,649	1		
550	0,745	0,786				0,679	0,791		
560	0,771	0,625				0,717	0,642		
570	0,761	0,528				0,761	0,579		
580	0,77	0,421				0,798	0,463		
590	0,824	0,194				0,841	0,164		
600	0,88	0,035	0,016			0,86	0,042	0,01	
610	0,906	0,007	0,257			0,875	0,009	0,234	
620	0,94	0,002	0,626			0,915	0,002	0,554	
630	0,978		0,882			0,946		0,847	
640	1		1			1		1	
650	0,978		0,652			0,99		0,763	
660	0,841		0,377			0,937		0,437	
670	0,768		0,144			0,866		0,199	
680	0,757		0,048			0,781		0,081	
690	0,744		0,021			0,717		0,033	
700	0,332		0,012			0,682		0,014	
710	0,138		0,007			0,66		0,007	
720	0,055		0,004			0,598		0,004	
730	0,022		0,003			0,21		0,003	
740	0,011					0,085			
750	0,005			0,022		0,036			0,058
760	0,003			0,106		0,017			0,175
770	0,002			0,318		0,009			0,397
780	0,001			0,614		0,005			0,672
790				0,855		0,002			0,889
800				0,978					0,993
810				1					1
820				0,965					0,864
830				0,91					0,8
840				0,862					0,767
850				0,808					0,75
860				0,748					0,657
870				0,4					0,416
880				0,189					0,187
890				0,066					0,069
900				0,024					0,022
910				0,006					0,007
920				0,004					0,003
930									

Table 20: SPOT2 Spectral sensitivities

SPOT4	HRVIR1					HRVIR2			
LAMBDA									
(nm)	B1	B2	B3	MIR		B1	B2	B3	MIR
470	0,000					0,000			
480	0,009					0,003			
490	0,160					0,156			
500	0,461					0,445			
510	0,718					0,712			
520	0,905					0,923			
530	0,984					0,995			
540	1,000					0,983			
550	0,995					0,907			
560	0,969					0,863			
570	0,927					0,812			
580	0,890					0,767			
590	0,855	0,000				0,643	0,000		
600	0,702	0,013				0,492	0,040		
610	0,464	0,247				0,278	0,350		
620	0,228	0,596				0,090	0,680		
630	0,082	0,816				0,032	0,870		
640	0,027	0,904				0,021	0,940		
650	0,010	0,952				0,006	0,990		
660		0,994					0,990		
670		0,957					0,830		
680		0,746					0,540		
690		0,448					0,270		
700		0,326					0,150		
710		0,126					0,080		
720		0,070					0,040		
730		0,038	0,000				0,020	0,000	
740		0,019	0,007				0,010	0,010	
750		0,010	0,039				0,000	0,040	
760			0,149					0,200	
770			0,387					0,390	
780			0,668					0,620	
790			0,856					0,780	
800			0,930					0,880	
810			0,937					0,920	
820			0,941					0,970	
830			0,965					1,000	
840			0,963					0,990	
850			0,935					0,970	
860			0,896					0,950	
870			0,869					0,910	
880			0,765					0,750	
890			0,570					0,510	
900			0,374					0,290	
910			0,208					0,140	
920			0,111					0,070	
930			0,054					0,040	
940			0,030					0,020	

950			0,010					0,010	
1510				0,003					0,000
1520				0,007					0,029
1530				0,011					0,056
1540				0,018					0,121
1550				0,035					0,251
1560				0,080					0,484
1570				0,162					0,663
1580				0,325					0,825
1590				0,643					0,984
1600				0,926					1,000
1610				0,997					0,977
1620				0,882					0,943
1630				0,806					0,956
1640				0,811					0,960
1650				0,834					0,896
1660				0,805					0,772
1670				0,723					0,654
1680				0,633					0,519
1690				0,509					0,353
1700				0,343					0,210
1710				0,209					0,123
1720				0,122					0,075
1730				0,073					0,052
1740				0,048					0,036
1750				0,032					0,024
1760				0,021					0,015
1770				0,014					0,010
1780				0,009					0,006
1790				0,007					0,006
1800				0,006					0,004
1810				0,004					0,001

Table 21: SPOT4 Spectral sensitivities

SPOT5	HRG1						HRG2				
LAMBDA											
(nm)	Pa	B1	B2	B3	MIR		Pa	B1	B2	B3	MIR
450	0,007	0,000					0,002	0,000			
455	0,004	0,000					0,001	0,000			
460	0,005	0,000					0,004	0,000			
465	0,017	0,000					0,015	0,000			
470	0,072	0,000					0,081	0,000			
475	0,193	0,000					0,239	0,000			
480	0,324	0,005					0,429	0,007			
485	0,463	0,039					0,604	0,054			
490	0,593	0,137					0,698	0,179			

495	0,710	0,299					0,756	0,372			
500	0,780	0,461					0,795	0,557			
505	0,806	0,595					0,832	0,696			
510	0,825	0,704					0,877	0,796			
515	0,856	0,787					0,919	0,865			
520	0,899	0,863					0,949	0,921			
525	0,943	0,920					0,964	0,963			
530	0,965	0,965					0,965	0,984			
535	0,980	0,990					0,969	1,000			
540	0,987	1,000					0,982	0,996			
545	0,985	0,992					0,990	0,978			
550	0,979	0,969					0,994	0,950			
555	0,964	0,926					0,990	0,905			
560	0,959	0,877					0,990	0,847			
565	0,953	0,820					0,989	0,790			
570	0,956	0,753					0,990	0,723			
575	0,963	0,685					0,996	0,661			
580	0,967	0,612	0,000				0,995	0,594	0,000		
585	0,968	0,535	0,000				0,988	0,526	0,000		
590	0,965	0,448	0,000				0,984	0,457	0,000		
595	0,962	0,347	0,000				0,979	0,378	0,000		
600	0,968	0,248	0,002				0,981	0,294	0,002		
605	0,982	0,156	0,019				0,991	0,205	0,022		
610	0,992	0,092	0,104				0,997	0,132	0,117		
615	0,997	0,050	0,298				1,000	0,077	0,315		
620	1,000	0,026	0,526				1,000	0,042	0,534		
625	0,996	0,013	0,714				0,991	0,022	0,705		
630	0,987	0,007	0,847				0,977	0,012	0,826		
635	0,976	0,004	0,926				0,961	0,007	0,902		
640	0,961	0,003	0,975				0,944	0,004	0,952		
645	0,943	0,000	0,995				0,927	0,000	0,980		
650	0,932	0,000	1,000				0,919	0,000	0,994		
655	0,910		0,987				0,897		1,000		
660	0,895		0,962				0,864		0,997		
665	0,869		0,924				0,790		0,982		
670	0,806		0,875				0,657		0,945		
675	0,678		0,815				0,476		0,863		
680	0,502		0,723				0,308		0,717		
685	0,327		0,595				0,186		0,534		
690	0,195		0,439				0,109		0,356		
695	0,114		0,293				0,066		0,223		
700	0,067		0,178				0,041		0,133		
705	0,039		0,105				0,026		0,079		
710	0,024		0,060				0,017		0,048		
715	0,016		0,035				0,011		0,029		
720	0,011		0,020				0,008		0,018		
725	0,000		0,011				0,000		0,011		
730	0,000		0,007				0,000		0,007		
735	0,000		0,004				0,000		0,004		
740	0,000		0,002				0,000		0,002		
745	0,000						0,000				
750	0,000			0,001			0,000			0,000	
755				0,004						0,005	

760				0,011						0,016	
765				0,030						0,043	
770				0,071						0,097	
775				0,143						0,184	
780				0,244						0,297	
785				0,370						0,434	
790				0,502						0,565	
795				0,630						0,691	
800				0,734						0,792	
805				0,821						0,873	
810				0,884						0,929	
815				0,938						0,965	
820				0,968						0,990	
825				0,985						0,998	
830				0,999						1,000	
835				1,000						0,991	
840				0,994						0,979	
845				0,973						0,961	
850				0,944						0,940	
855				0,918						0,922	
860				0,887						0,891	
865				0,856						0,869	
870				0,803						0,815	
875				0,733						0,734	
880				0,630						0,613	
885				0,494						0,458	
890				0,370						0,327	
895				0,249						0,217	
900				0,157						0,134	
905				0,103						0,087	
910				0,066						0,058	
915				0,041						0,036	
920				0,027						0,024	
925				0,019						0,017	
930				0,012						0,011	
935				0,008						0,008	
940				0,006						0,005	
945				0,004						0,000	
950				0,003						0,000	
1500					0,000						0,000
1505					0,000						0,000
1510					0,000						0,000
1515					0,000						0,000
1520					0,018						0,011
1525					0,023						0,015
1530					0,029						0,019
1535					0,038						0,025
1540					0,047						0,031
1545					0,065						0,043
1550					0,083						0,056
1555					0,125						0,088
1560					0,167						0,120

1565					0,242						0,183
1570					0,315						0,247
1575					0,403						0,331
1580					0,489						0,415
1585					0,575						0,513
1590					0,663						0,610
1595					0,760						0,723
1600					0,856						0,836
1605					0,932						0,918
1610					1,000						1,000
1615					0,994						0,995
1620					0,991						0,988
1625					0,933						0,932
1630					0,879						0,878
1635					0,864						0,858
1640					0,842						0,835
1645					0,868						0,859
1650					0,893						0,883
1655					0,893						0,895
1660					0,840						0,905
1665					0,772						0,849
1670					0,690						0,792
1675					0,607						0,686
1680					0,529						0,578
1685					0,446						0,468
1690					0,366						0,359
1695					0,290						0,287
1700					0,227						0,214
1705					0,166						0,172
1710					0,127						0,129
1715					0,086						0,101
1720					0,066						0,074
1725					0,046						0,058
1730					0,036						0,042
1735					0,026						0,034
1740					0,022						0,026
1745					0,018						0,021
1750					0,015						0,017
1755					0,012						0,014
1760					0,009						0,011
1765					0,007						0,009
1770					0,005						0,007
1775					0,004						0,005
1780					0,003						0,004
1785					0,002						0,003
1790					0,002						0,003
1795					0,001						0,002
1800					0,001						0,002

Table 22: SPOT5 Spectral sensitivities