DAWN VIR CALIBRATION DOCUMENT

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Document Change History

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Version 2.0	October 2013	Chapter 6 : added details about the responsivity formula. Chapter 7 : added some explanation about usage of internal calibration Chapter 8 : added details about the dark current subtraction procedure, corrected CALIB directory file names.	M. GIARDINO (INAF-IAPS, Rome)	M.C. DE SANCTIS (INAF-IAPS, Rome) M.T. CAPRIA (INAF-IAPS, Rome)
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Version 2.5	January 2016	Chapter 8: added the name of the PDS field containing the integration time; added information about the ITF file format.	M. GIARDINO (INAF-IAPS, Rome)	M.C. DE SANCTIS (INAF-IAPS, Rome) M.T. CAPRIA (INAF-IAPS, Rome)

1. INTRODUCTION

This document describes the algorithms used to calibrate VIR raw (EDR) data in physical units (RDR, spectral radiance), in order to give to the final user a detailed view of the methods used to remove instrumental effects on the data. A complete calibration campaign of VIR was performed at the channel level in Selex Galileo (SG), Florence by using a variety of calibration facility setups. These calibrations were performed immediately after instrument assembly and before delivery to Orbital for integration with the Dawn spacecraft. The SG calibration included spectral, geometrical, flat-field and radiometric measurements as well as characterization of the detectors performance (including defective pixels, linearity and dark current at various operative temperatures), the instrumental thermomechanical stability, the data-commanding-telemetry handling and electrical interfaces. A description of the methods used and results of these tests are described in De Sanctis et al. (2010).

Section 2 describes the experimental setup used for pre-lauch calibrations at SG; section 3 is devoted to the description of the spectral calibration; geometrical calibration is included in section 4; flat-field is described in section 5; section 6 contains a description of radiometric calibration; section 7 is about the internal calibration procedure and finally section 8 explain the algorithms used to convert raw data in spectral radiance or reflectance.

2. CALIBRATION SETUP

The basic setup used during the calibrations consists of an optical bench over which are housed a collimator, a reference target placed at its focal plane and a folding mirror used to move the collimated beam in the instrumental FOV along the azimuthal (sample) and zenithal (line) directions. Since VIR focuses at infinite distance it becomes necessary to use a collimator to have a collimated reference beam impinging the optical pupil. The SG-developed collimator uses an off-axis parabola (D=250 mm, F=1020 mm, off axis angle=8°) which guarantees an unobstructed beam, reduced aberrations and high spatial scale. For VIR the magnification ratio is equal to:

$$MR=F\_VIR/F\_collimator=152mm/1020mm=0.15$$

This means that 1 mm on the collimator's focal plane corresponds to 0.15 mm on the VIR focal plane. The VIR detector has a 40 µm pixel pitch (square), so this scale corresponds to 4 spatial pixels along both sample and line directions. The collimator's focal plane is equipped with a holder able to sustain several interchangeable targets (pinholes, test slits, MTF masks, and a matrix of 5x5 microlamps). These elements are used to perform the different calibrations. The collimated beam is folded towards the instrument by using a folding mirror placed over two computer controlled, micrometric mounts able to aim it with steps of 1 µrad along the azimuthal (scan parallel to VIR slit, along sample direction) and zenithal (scan perpendicular to the slit, along lines direction) angles.

During the calibration the VIR instrument is housed in a thermo-vacuum chamber in order to reproduce the operating conditions aboard the satellite, In these conditions it's possible to cool the IR detector down to the operating temperature of about 70 K by using the cryo-cooler (operating on a Stirling cycle) and the CCD at about 160 K by using a passive radiator.The collimated optical beam reaches the spectrometer's pupil through a CaF2 window housed in the front of the thermos-vacuum chamber. This window is characterized by an elevated optical transmittance in the 250-5100 nm spectral range.

All opto-mechanical devices placed on the optical bench are controlled by using a dedicated software (OCS, Optical Control System), while the VIR instrument is controlled by using a separate setup, consisting in the UT (Unit Tester) connected to the experiment through the Proximity Electronics Module (PEM). This system allows the sending of commands to the instrument, to start acquisitions only when all optical elements commanded by OCS are in the correct configuration and to receive back and record telemetry and calibration data.

3. SPECTRAL CALIBRATION

The spectral calibration characterizes a fundamental aspect of the functional requirements of a hyperspectral imaging spectrometer: the conversion of bands positions along the spectral axis of the detectors into wavelength units.The spectral calibration is obtained through the following steps:

- characterization of the spectral performances of the monochromator to be used as a calibrated reference source; this preliminary check was performed on the emission features of a standard Hg pencil lamp;
- use of the monochromator to scan in detail a subset of the spectral range and measure the corresponding instrumental spectral response;
- fit of these spectral responses with gaussian curves to retrieve the channel’s parameters;
- extension of these values to the remaining bands with a linear fit.

The following instrumental parameters are deduced from the spectral calibration:

- Spectral range: the interval of wavelengths over which the instrument is sensitive;
- Sample Central Wavelength: the VIS and IR Sample Central Wavelength, $\lambda_{VIS}(m, n)$ and $\lambda_{IR}(m, n)$, is the wavelength of the centroid of the Spectral Response Function for each frame pixel (m, n), where m is the frame sample (row) index and n is the frame band (column) index;
- Spectral Sampling Interval: the VIS and IR Spectral Sampling Interval, $SSI_{VIS}(m, n)$ and $SSI_{IR}(m, n)$, is the difference between the VIS and IR sample central wavelengths of two adjacent samples for each frame pixel (m, n), where m is the frame sample (row) index and n is the frame band (column) index;
- SpectralWidth: the VIS and IR Spectral Widths, $SW_{VIS}(m, n)$ and $SW_{IR}(m, n)$, are the Full-Width-at Half-Maximum of the Spectral Response Function for each frame pixel (m, n), where m is the frame sample (row) index and n the frame band (column) index.

Because the instrument uses a diffraction grating that disperses the light according to a linear law we can assume SSI(n) = SSI; in this case the spectral calibration relation assumes the following expression:

$$\lambda_c(n) = \lambda_0 + SSI \cdot b$$

These quantities were measured during the ground calibration by acquiring several fine spectral scans using a monochromator as a source. The calibration setups used to define the spectral properties of VIR using a heritage setup developed for the VIRTIS/M aboard Rosetta and the Venus Express missions (Ammannito et al. 2006; Filacchione et al. 2006). Two different configurations were used to characterize the spectral response, the first using a transmission method and the second using a diffusion method. In the first case (transmission) on the optical bench, the source, the monochromator, the test slit and the collimator were present; using this set-up the level of the signal was high enough to stimulate VIR, but the alignment between the output slit of the monochromator and the test slit of the optical bench was difficult to achieve. In the second case (diffusion) the source, the monochromator, a silvered diffusive target and the collimator were on the bench. In this case the alignment of the system wasn’t critical, but the level of the signal was lower. The monochromator scans different wavelengths, thus illuminating the diffusive screen. VIR acquires monochromatic images at each step. Therefore VIR is "simulated" at wavelength steps smaller than its spectral resolution. In this way it is possible to associate to each frame the wavelength of the input beam coming from the monochromator. Studying the profile over the lines of each illuminated band, it is possible to get the spectral response function of that particular band.

3.1 Transmission method

The transmission method was applied only to the visual channel. For each illuminated pixel, the spectral response function was computed by fitting a Gaussian-like function over the profiles measured during the spectral scans. With this setup the intensity of the signal along the slit isn't uniform. This could be related to a misalignment between the output slit of the monochromator, the test slit of the optical bench in particular, and the entrance slit of the experiment. Moreover on the optical bench were a spectral shift along the slit is apparent, given that at every illuminated band a different central wavelength is found. The central wavelength and the spectral width of the illuminated bands are calculated by averaging such parameters over every illuminated sample. The central wavelength of the band is calculated by using a linear fit while the spectral width is given by a polynomial fit. A summary of the parameters calculated with the fits and their uncertainties are reported in the following table:

	Spectral dispersion	Spectral width
Model	$a \cdot x + b$	$a \cdot x^4 + b \cdot x^3 + c \cdot x^2 + d \cdot x + e$
Parameters	a = 1.89297 b = 245.744	a = 5.25E–11 b=−6.08E–8 c = 2.74E–5 d =−0.0049 e = 2.13
Sigma	σa = 0.00016 σb = 0.041	σa = 0.14E–11 σb = 0.14E–7 σc = 4.82E–5 σd = 0.0068 σe = 0.31

In the next table are indicated, for all the illuminated bands, the measured and calculated values of the central wavelength and spectral width. The measured values are averages computed over all the illuminated samples for a fixed band.

Band #	λmeas (nm)	λcal (nm)	SWmeas (nm)	SWcal (nm)
79	395.125	395.289	1.89559	1.88451
80	397.049	397.182	1.89332	1.88290
81	398.964	399.075	1.88235	1.88131
82	400.860	400.967	1.87189	1.87976
83	402.761	402.860	1.86246	1.87824
84	404.662	404.753	1.87010	1.87675
157	542.828	542.94	1.87158	1.82947
158	544.925	544.833	1.84376	1.82947
159	546.835	546.726	1.83146	1.82949
160	548.742	548.619	1.82906	1.82952
161	550.640	550.512	1.82154	1.82956
162	552.548	552.405	1.84028	1.82961
163	554.454	554.298	1.84128	1.82967
237	694.480	694.378	1.81275	1.85861
238	696.323	696.271	1.86955	1.85922
239	698.219	698.164	1.84252	1.85983
240	700.101	700.057	1.85477	1.86045
241	702.000	701.950	1.86519	1.86107
242	703.898	703.843	1.85821	1.86170
317	845.842	845.816	1.91248	1.91559
318	847.74	847.709	1.91959	1.91639
319	849.647	849.602	1.92232	1.91720
320	851.542	851.495	1.91718	1.91800
321	853.447	853.388	1.91865	1.91881
396	995.282	995.361	1.97795	1.99122
397	997.171	997.254	1.98837	1.99243
398	999.063	999.147	1.99155	1.99365
399	1000.95	1001.04	1.98800	1.99487
400	1002.85	1002.93	2.00388	1.99611
401	1004.75	1004.83	2.00954	1.99735

From the analysis of measurements we have noted the presence of a slight spectral shift occurring along the slit. In order to evaluate this effect we repeated the calculation of the linear fit coefficients for other samples along the slit (at samples = 110, 140); previously, the results at slit's center (sample = 128) were discussed. This analysis demonstrates the presence of a change in the spectral calibration response when repeated on different points along the slit. The fit parameters with their errors on samples 110, 128, 140 are reported in the following table.

Sample #	λ_{meas} (nm)	SW_{meas} (nm)
110	246.76 ±0.56	1.8926 ± 0.0022
128	245.83 ±0.30	1.8926 ± 0.0011
140	245.40 ±0.19	1.8921 ± 0.0007

These calculations demonstrate that the parameters are mutually incompatible so the central wavelengths calculated with the coefficients indicated in the previous table cannot be used and another calibration approach is necessary. At the end of the post-processing analysis it was concluded that the measurements of the spectral width are satisfactory while further measurements are needed to determine the dispersion coefficients. Using the Transmission setup, in fact, they seem to be sample dependent. In the next paragraph the results obtained using the Diffusion setup data are discussed.

3.1 Diffusion method

The Diffusion method was used to characterize the spectral response of both the Visual and the Infrared channels. We use these measurements to determine the central wavelength of the Visual channel and both the central wavelength and the spectral width of the Infrared channel. Comparing these results with the similar profiles taken with the Transmission setup, it is apparent that the spectral shift among profiles taken at different samples is negligible. In this way it is verified that the effect is caused by the Transmission set-up characteristics (difficult to co-align VIR and test slit orientations) and is not due to the VIR malfunctioning.
By using the same technique discussed in advance, we have retrieved the best spectral dispersion and width values. For both channels, the central wavelength of each band b is retrieved through a linear fit while for the spectral width is used a polynomial fit.

	Spectral dispersion	Spectral width
VIS	Model $a \cdot x + b$	$a \cdot x^4 + b \cdot x^3 + c \cdot x^2 + d \cdot x + e$
Parameters	a = 1.89223 b = 245.660	a = 1.3E–10 b=−1.1E–7 c = 1.89E–5 d = 0.0047 e = 1.6
Sigma	σa = 0.00033 σb = 0.085	σa = 8.1E–10 σb = 7.8E–7 σc = 0.26–5 σd = 0.0037 σe = 1.7
IR	Model $a \cdot x + b$	$a \cdot x^4 + b \cdot x^3 + c \cdot x^2 + d \cdot x + e$
Parameters	a = 9.4593 b = 1011.29	a =−6.8E–10 b = 8.23E–7 c=−2.09E–4 d = 0.0021 e = 13.9
Sigma	σa = 0.0011 σb = 0.28	σa = 2.3E–9 σb = 1.6E–6 σc = 3.80E–4 σd = 0.0335 σe = 1.2

We report in the next Table the measured and computed values of the central wavelength and spectral width for both channels. The measured values are averaged over all the samples for a given band.

VIS channel

Band #	λ_{meas} (nm)	λ_{cal} (nm)	SW_{meas} (nm)	SW_{cal} (nm)
81	398.875	398.931	2.07338	2.03109
82	400.774	400.823	2.02554	2.03699
83	402.597	402.715	1.99148	2.04287
84	404.436	404.607	2.07068	2.04875
158	544.700	544.633	2.42099	2.44303
159	546.577	546.525	2.44812	2.44754
160	548.465	548.417	2.45310	2.45203
161	550.355	550.309	2.45829	2.45648
162	552.249	552.201	2.47181	2.46091
163	554.144	554.094	2.47652	2.46531
164	556.028	555.986	2.46822	2.46969
238	696.007	696.011	2.69859	2.70952
239	697.892	697.903	2.69611	2.7116

240	699.785	699.795	2.69541	2.71365
241	701.677	701.688	2.70452	2.71567
242	703.572	703.58	2.72082	2.71767
243	705.508	705.472	2.80885	2.71963
317	845.453	845.497	2.75994	2.79344
318	847.337	847.389	2.80736	2.79368
319	849.239	849.282	2.8061	2.79391
320	851.142	851.174	2.79165	2.79412
321	853.043	853.066	2.80487	2.79433
396	994.789	994.983	2.75589	2.80388
397	996.686	996.875	2.8257	2.80439
398	998.595	998.768	2.77639	2.80492
399	1000.46	1000.66	2.79735	2.80548
400	1002.28	1002.55	2.78868	2.80606
401	1004.22	1004.44	2.84745	2.80666

IR channel

Band #	λ_{meas} (nm)	λ_{cal} (nm)	SW_{meas} (nm)	SW_{cal} (nm)
2	1029.3	1030.21	14.0742	13.9467
3	1038.77	1039.67	13.78	13.9478
103	1986.31	1985.6	12.9869	12.7654
104	1995.85	1995.06	12.7585	12.7477
105	2005.35	2004.52	12.6494	12.7299
106	2014.87	2013.98	12.5963	12.7122
208	2978.82	2978.83	11.4667	11.4689
209	2988.07	2988.29	11.2923	11.4666
210	2997.45	2997.75	11.6996	11.4645
211	3006.83	3007.21	11.5063	11.4626
212	3016.13	3016.67	11.337	11.461
315	3991.6	3990.98	12.7906	12.9028
316	4000.3	4000.44	12.6859	12.9335
317	4010.2	4009.9	13.5031	12.9647
367	4482.68	4482.86	14.9175	14.9333
368	4492.2	4492.32	15.1484	14.9807
369	4501.56	4501.78	14.8612	15.0283
370	4511.02	4511.24	15.1136	15.0763

Following the post-processing analysis we find that the measurements of the dispersion coefficients are good for both the visual and infrared focal planes, that measurements of the spectral width for the infrared focal planes are compliant with the specifications, and that the spectral width of the visual focal plane, the one computed with the transmission method, gives better results. The quality of the spectral calibration is confirmed by observing the spectrum of a calibrated HgNe pencil lamp.

4. GEOMETRIC CALIBRATION

The geometrical calibration allows characterization of:

1. the field of view, hereafter FOV;
2. the instantaneous field of view (hereafter IFOV) of different pixels along and across the spectrometer's slit directions (respectively sample and line directions).

We define the pixel function, PF(s), as the convolution of a unitary step function V (s) (representing the real pixel) with the instrumental response along the sample direction, INST(s):

$$PF(s) = V(s) \otimes INST(s)$$

The slit function, SF(l), is given by the convolution of a unitary step function U(l) (representing the spectrometer's slit response) with the telescope response along the line direction, TEL(l):

$SF(l) = U(l) \otimes TEL(l)$

These two responses were measured during the pre-launch calibration campaign acquiring the signal produced by a test-slit, illuminated by a HgNe lamp, having an equivalent width narrower than the instrumental IFOV (the test slit aperture is 3.0 x 0.1 mm, corresponding to 12 x 0.4 pixels at VIR scale). This test-slit is placed at the collimator's focus and it is moved at subpixel steps perpendicular and parallel to the VIR slit by moving the folding mirror. By using this method it is possible to measure the FWHM of the IFOV at three positions of the FOV (boresight: sample = 128, line = 128), position N: sample = 38, line = 218; position O: sample = 218, line = 38). For the VIS channel the FWHM of the pixel function is ranges over the 237.9–244.1 μrad interval while the slit function is 287.7–389.4 μrad; for the IR channel the ranges are 421.7–488.1 and 350.9–367.3 μrad respectively. These differences are caused by a residual of astigmatism in the optical design.

The determination of the FOV (nominally 3.6° x 3.6°) is possible through the imaging of a 5 x 5 array of microlamps placed at the focus of a collimator. This array was built to cover the entire FOV when placed at collimator's focus: the presence of a regular grid of subpixel sources allows for evaluation of the imaging and geometrical performances of the experiment. The absolute position of each microlamp was measured with a theodolite placed on the pupil of the collimated beam; when compared to the relative positions of the lamps spots on the images it is possible to infer the dimensions of the instrumental FOV.

Moreover, this setup is particularly useful in evaluating the presence of possible "spectral shift", e.g. a mismatch between the position of one monochromatic image with respect to another. This effect is particularly evident on VIRTIS-M on Rosetta, where it reaches a shift of about 8 spatial pixel (samples) between the first and the last image of the VIS channel. The cause of it is a slight misalignment among slit, grating grooves and focal plane orientation (for a full discussion of the spectral tilt and post-processing corrective methods the reader can refer to Filacchione 2006). For VIR several optical improvements were introduced on the grating design that allow drastically reducing this effect. Analysis of the 25 microlamp target data allows verification that the spectral shift on the VIS channel reaches about 2 spatial pixels between the two spectral extremes of the range. This value comes from the analysis of the distribution of the microlamps position (in sample-line space) on the monochromatic images. As each microlamp has a subpixel dimension when seen by VIR through the optical bench setup, it is possible to measure the associate barycenter position through a 2D Gaussian fit; this procedure is done for each lamp and for every spectral band (432 images).

5. SPATIAL CALIBRATION: FLAT-FIELD

Flat-field is defined as the response of the instrument to a uniform source (Filacchione et al. 2006). It is used to homogenize the pixels' response across the whole focal plane. In the case of imaging spectrometers using 2D detectors, flat field matrices contain, for each wavelength, the relative variation of the instrumental response with respect to the boresight (sample $s^* = 127$).

The measurements of the VIS and IR flat-field matrices were calculated during the pre-launch tests by acquiring a spatially flat source placed on the focus of a collimator and aligned to the VIR boresight. The source used in the 0.25–2.5 μm range is a Lambertian surface illuminated by a QTH lamp; this target is about 10 x 10 cm wide in order to completely fill the instrumental FOV. It is replaced by a blackbody source for the measurement of the flat-field in the 2.5–5.0 μm range. In both cases the flat field is retrieved through a spatial scan across these targets by moving the folding mirror at 1 IFOV step. This approach allows for observation of the same region of the target with each pixel (sample) of the detector, thus eliminating possible target non-uniformity from the flat-field matrices.

The resulting flat-field matrices for the two focal planes are given by the ratio of the signal measured at a certain position of the focal plane (b, s) with respect to the signal measured at boresight ($s = s^*$) and at the same band position b:

$$FF(b,s) = N_s(b,s) / N_s(b, s^*)$$

Flat-field matrices are sensitive to the characteristics of the detector (single and clusters of defective pixels, dis-uniformities due to the production process) and of the optical layout (the two horizontal features at samples 80 and 150 are caused by the slit's shape; several vertical features with a symmetry with respect to boresight are introduced by the grating design).

6. RADIOMETRIC CALIBRATION

As explained in the Flat-Field paragraph, the wide spectral range of the experiment can only be explored by using different sources (Filacchione et al., 2006). For the radiometric calibration two different sources are necessary:

- 0.25–1.0 µm: QTH source, with photometric stabilization system, illuminating a diffusive target in Spectralon™ placed at collimator's focus;
- 1.0–5.0 µm: Blackbody at variable temperature (from 50° to 350°C) with temperature control. The BB emitting area is placed at collimator's focus.

The input radiance is measured and verified through a laboratory radiometer, (Field-Spec™ spectroradiometer). Unfortunately as the optical pupil of the Field-Spec optics does not match entirely with the VIR pupil, the measured radiance can only be used as a relative value: the "shape" of the radiance, Rad, emitted by the target doesn't change but the knowledge on the geometric factor (constant and uniform for each spectral channel) is not known. For this reason the overall calibration shall be tested in flight and complemented with specific observations of known targets, such as stars and planets. The lamps used are observed first with the spectroradiometer, and then with VIR. Knowing the value of input radiance, we can associate it with an average of 50 VIR acquisitions of the Spectralon™ target, taken at slit center, with an integration time
ti = 10 s. The Responsivity, R, is therefore calculated by applying the following equation:

$$R(b, s^*) = DN(b, s^*) / (BB(b) * t_i)$$

where R(b,s*) is the responsivity computed for each band b at the sample s*, DN(b,s*) is the raw signal in digital numbers acquired by the spectrometer for each band b at the sample s*, BB(b) is the radiance of the source measured by the reference spectroradiometer and sampled at the VIR spectral band b and t_i is the integration time.

The expansion to the sample of the focal plane different from s* is possible applying the flat-field FF. In this way we retrieve the ITF (Instrument Transfer Function) array:

$$ITF(b, s) = FF(b, s) \cdot R(b, s^*)$$

The IR channel radiometric calibration is done acquiring directly the radiance emitted by a blackbody source placed at the collimator's focus. The blackbody temperature is set at different values in order to have a good SNR on several spectral ranges and with different integration times (a summary of the acquisitions is given below). As reported in the next Table, only a limited spectral range can be used for the evaluation of the IR responsivity: for bands < Min Band the signal is very low and it includes only the readout offset and residuals of the dark current; for bands > Max Band value the signal is saturated. After this selection we reduce the signals in the restricted spectral range Min Band < band < Max Band; therefore the responsivity is retrieved by using only the signal intervals as indicated in following:

TBB (°C)	ti (s)	Min Band	Max Band
50	0.2	250	438
	1.0	238	280
	2.0	238	255
	5.0	170	240
100	0.2	238	281
	1.0	148	239
	2.0	140	195
	5.0	120	170
200	0.2	110	174
	1.0	80	120
	2.0	70	105

	5.0	65	95
300	0.2	60	100
	1.0	40	68
	2.0	35	58
	5.0	0	37
350	0.2	0	78
	1.0	0	52
	2.0	0	35

The IR responsivity is computed by using:

$R(b, s^*) = DN(b, s^*) / (BB(b) * t_i)$

where the blackbody radiance BB is given by Planck's formula. Finally, applying

$ITF(b, s) = FF(b, s) \cdot R(b, s^*)$

to these data, it is possible to derive the responsivity for each pixel of the IR channel.

7. INTERNAL CALIBRATION

Instrumental performances can be checked during in-flight conditions by using the internal calibration sequence. VIR can acquire reference signals by using the combination of the cover, shutter and VIS and IR lamps (Melchiorri et al., 2003). These lamps, housed on the side of the telescope illuminate the internal side of the external cover. The cover is placed near the entrance pupil of the instrument to minimize optical aberrations. The window of each lamp contains a transparent filter (holmium for the VIS, polystyrene for the IR) to introduce some well-shaped spectral absorption features on the overall spectrum. The signal coming from the two lamps can be used to:

- check the in-flight stability of the instrumental spectral response;
- check the in-flight stability of the flat-field;
- monitor the evolution of defective pixels (number and distribution);
- perform a check on the relative radiometric response of the instrument.

The internal calibration mode, implemented in the VIR on-board software, consist in the acquisition of a sequence of 35 frames: 5 electronic offsets, 5 backgrounds, 5 dark currents, 5 acquisitions of the IR lamp, 5 acquisitions of the VIS lamp, 5 dark currents and 5 backgrounds. Even if the data acquired during this sequence are not used in the calibration pipeline, they are fundamental to follow the temporal evolution of the instrument and to monitor the overall performances in operative conditions.

8. HOW TO CALIBRATE VIR IN-FLIGHT DATA

The VIR team receives data and telemetry packets from the satellite from the Dawn Science Center (UCLA-JPL). These packets are processed at the PI institution (INAF-IFSI, Rome, Italy) with a proprietary GSE (Ground Support Equipment) and converted into standard PDS (Planetary Data System) format. A dedicated package scripts and routines and calibration files distributed with this archive are used to convert the raw data in physical units.

A raw data cube contains uncalibrated signal N_s in DN; dark currents are periodically stored in the same raw data cube and in each data cube there is at least one dark current acquisition. The dark current must be subtracted from the original data in the raw cube before the conversion in physical units. The number and location of dark current frames in each raw cube is documented in the hkt table (shutter status, open if normal acquisition, closed if dark current acquisition). The same information alternatively can be found by reading the parameter DARK_ACQUISITION_RATE into the data cube label file.

Raw data cubes may have one or more dark current frames. If there is only one dark current frame in a raw data cube, the equivalent dark current frame is the same for every frame in the data cube and is equal to the only dark current frame acquired, If there is more than one dark current frame, the equivalent dark current frame is the interpolation in time of two consecutive acquired dark frames. The dark subtracted frames are computed subtracting the equivalent dark current frame to the original frame in the raw data cube. At the end of this operation the dark current frames are removed and there will be a dark subtracted data cube with the same bands and samples number of the raw data cube and a number of lines equal to the original minus the number of dark current frames. This is the reason why calibrated cubes have a lower number of frames than the corresponding raw cubes.

The counts stored in the PDS cube can be converted in physical units of spectral radiance Rad (W m^{-2} μm^{-1} $sterad^{-1}$) by using the following equation:

$S(\lambda(b), x, y) = N_s(b, s, l) / (ITF(\lambda(b), s) * t_i)$

where:

-S(λ(b),s,l) is the cube calibrated in spectral radiance which have the same bands and samples number of the raw data cube and a number of lines equal to the original minus the number of dark current frames of the raw cube;

-λ(b) is the wavelength associated to band b according to spectral calibration tables of VIS and IR channels (files DAWN_VIR_VIS_HIGHRES_SPECAL_Vx.TAB and DAWN_VIR_IR_HIGHRES_SPECAL_Vx.TAB, respectively);

-s, l corresponds to sample and line location of the pixel in the dark subtracted cube;

-t_i is the integration time of the observations (in seconds) as indicated in the field FRAME_PARAMETER .EXPOSURE_DURATION of PDS header of the file for VIS and IR channels;

-ITF(λ(b), s) is the Instrument Transfer Function matrix for VIS and IR channels (files DAWN_VIR_VIS_RESP_Vx.DAT and DAWN_VIR_IR_RESP_Vx.DAT, respectively).

At the same time, to calculate the calibrated reflectance factor, the equation is:

$R(\lambda(b), x, y) = (S(\lambda(b), x, y) * (\pi * (ssd / K)^2)) / si$

where

-R(λ(b), x, y) is the cube calibrated reflectance factor which have the same bands and samples number of the raw data cube and a number of lines equal to the original minus the number of dark current frames of the raw cube;

- K is the value of one astronomical unit expressed in km (149597870.7) ;

-ssd is the spacecraft heliocentric distance expressed in km, as read from the cube label file in the SPACECRAFT_SOLAR_DISTANCE field;

- si is the solar irradiance for VIS and IR channels (files DAWN_VIR_VIS_SOLAR_SPECTRUM_Vx.DAT and DAWN_VIR_IR_SOLAR_SPECTRUM_Vx.DAT, respectively).

These calculations can be applied to high resolution acquisitions (432 bands times 256 samples); in nominal modes, where spatial and/or spectral resolutions are reduced, it is necessary to interpolate both spectral tables and responsivity matrices according to binning values.

The following calibration files are stored in the CALIB directory of the PDS archives:

- DAWN_VIR_VIS_RESP_V*x*.DAT, a 432x256 floating precision matrix containing the VIR-VIS Instrumental Transfer Function, including the VIS flat-Field. The file format is binary, matrix values are stored using double precision floating point precision, band interleaved (PDS type is IEEE_REAL with 8 bytes length)

- DAWN_VIR_IR_RESP_V*x*.DAT, 432x256 floating precision matrix containing the VIR-IR Instrumental Transfer Function, including the IR flat-Field.

- DAWN_VIR_VIS_HIGHRES_SPECAL_V*x*.TAB and

- DAWN_VIR_IR_HIGHRES_SPECAL_V*x*.TAB, 432 row ASCII tables containing the wavelengths of the VIS and IR channels in High Resolution Mode.

- DAWN_VIR_VIS_WIDTH432_V*x*.TAB and

- DAWN_VIR_IR_WIDTH432_V*x*.TAB, 432 row ASCII tables containing the width of the VIS and IR channels in High Resolution Mode.

These files must be used for cubes collected in High Resolution Mode.

Cubes in Nominal Mode (x3 binning along bands) can be calibrated by using the following spectral calibration files:

- DAWN_VIR_VIS_NOMRES_SPECAL_V*x*.TAB and

- DAWN_VIR_IR_NOMRES_SPECAL_V*x*.TAB, 144 row ASCII tables containing the wavelengths of the VIS and IR channels in Low Resolution Mode.

- DAWN_VIR_VIS_WIDTH144_V*x*.TAB and

- DAWN_VIR_IR_WIDTH144_V*x*.TAB, 144 row ASCII tables containing the width of the VIS and IR channels in Low Resolution Mode ("*x*" is a digit representing the version number of the file). The first release is "V1".

VIR data included in this release can be calibrated by using this basic pipeline. Further improvements, based on the use of the internal calibration sequences, will be included in the next future. The actual ITF is also currently under improvement: calibrated values in the spectral range [2.534µm - 3.272µm] are still under verification, this is the reason why these values have been put to null into the ITF. When the validation tests will be completed, the next versions of ITF will be released. An alternative non-standard calibration procedure, based on external data derived from ground observations, can be found in [7].

9. REFERENCES

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