

DAWN VIR CALIBRATION DOCUMENT

Version 2.9 (December 2017)

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Document Change History

Change	Date	Affected Portions	Checked by	Approved by
Version 1.0	January 2011			A. CORADINI (INAF-IAPS, Rome)
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)
Version 2.1	November 2013		M. GIARDINO (INAF-IAPS, Rome)	M.C. DE SANCTIS (INAF-IAPS, Rome) M.T. CAPRIA (INAF-IAPS, Rome)
Version 2.4	May 2014	Chapter 8: added the formula to calculate the calibrated reflectance factor	M. GIARDINO (INAF-IAPS, Rome)	M.C. DE SANCTIS (INAF-IAPS, Rome) M.T. CAPRIA

				(INAF-IAPS, Rome)
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)
Version 2.6	October 2016	Chapter 4: changed denomination from spectral shift to spatial shift Chapter 8: added description of the detilt algorithm for the visible channel	M. GIARDINO (INAF-IAPS, Rome)	M.C. DE SANCTIS (INAF-IAPS, Rome)
Version 2.7	February 2017	Chapter 8: added explanation about the parameters used in the detilt algorithm; updated the spectral and temporal range affected by the ITF null values	E. AMMANNITO M. GIARDINO (INAF-IAPS, Rome)	M.C. DE SANCTIS (INAF-IAPS, Rome)
Version 2.8	September 2017	Chapter 7: added description of internal calibration procedure. Created the new chapter 8 containing the description of the calibration refinement obtained with the last ITF. Previous chapter 8 (“how to calibrate vir in-flight data”) has been changed to chapter 9, while previous chapter 9 (“references”) has been changed to chapter 11. Chapter 9: added an explanation about the presence of contamination across campaigns. Created chapter 10 containing the listing of known instrument artifacts and their effects on data usability Chapter 11: added a new reference	E. AMMANNITO M. GIARDINO (INAF-IAPS, Rome)	M.C. DE SANCTIS (INAF-IAPS, Rome)
Version 2.9	December 2017	General revision applied, during the PDS peer review performed on the Ceres	E. AMMANNITO M. GIARDINO	M.C. DE SANCTIS (INAF-IAPS, Rome)

		<p>volumes between July and December 2017</p> <p>The internal calibration steps have been further documented by inserting a table in Chapter 7.</p> <p>In Chapter 9, the change operated to the execution cycle of the instrument to avoid the contamination found in VSH and VH2 is described.</p>	(INAF-IAPS, Rome)	
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1. INTRODUCTION

This document describes the algorithms used to calibrate VIR raw (EDR) data to data in physical units (RDR, spectral radiance), in order to give 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' performances (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. (2011).

Section 2 describes the experimental setup used for pre-launch 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; section 8 describes an in-flight instrument response function update using the onboard lamp to improve the calibration in the spectral range 2.5 μm - 3.5 μm ; and finally section 9 explains the algorithms used to convert raw data into 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 ($D=250\text{ mm}$, $F=1020\text{ mm}$, off axis angle= 8°), which guarantees an unobstructed beam, reduced aberrations, and high spatial scale. For VIR the magnification ratio is equal to:

$$MR = F_{\text{VIR}} / F_{\text{collimator}} = 152\text{mm} / 1020\text{mm} = 0.15$$

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 μ rad 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 to 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 thermo-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 of 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;
- Spectral Width: 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 for the spectral dispersion of the central wavelength:

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

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 used 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 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	$\sigma_a = 0.00016$	$\sigma_b = 0.041$	$\sigma_a = 0.14E-11$	$\sigma_b = 0.14E-7$	$\sigma_c = 4.82E-5$
			$\sigma_d = 0.0068$	$\sigma_e = 0.31$	

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 #	λ_{meas} (nm)	λ_{cal} (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 the 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 \pm 0.56	1.8926 \pm 0.0022
128	245.83 \pm 0.30	1.8926 \pm 0.0011
140	245.40 \pm 0.19	1.8921 \pm 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.

3.2 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 VIS 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. Using the same technique discussed previously, 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 a polynomial fit is used.

	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	$\sigma_a = 0.00033$ $\sigma_b = 0.085$	$\sigma_a = 8.1E-10$ $\sigma_b = 7.8E-7$ $\sigma_c = 0.26E-5$ $\sigma_d = 0.0037$
	$\sigma_e = 1.7$	
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	$\sigma_a = 0.0011$ $\sigma_b = 0.28$	$\sigma_a = 2.3E-9$ $\sigma_b = 1.6E-6$ $\sigma_c = 3.80E-4$ $\sigma_d = 0.0335$
	$\sigma_e = 1.2$	

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 compliant with the specifications for both the visual and infrared focal planes. For the VIS channel, computation with the diffusion method gives better results than computation with the transmission method. The quality of the spectral calibration was 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 ranges over the 237.9–244.1 μ rad interval while the slit function is 287.7–389.4 μ rad; for the IR channel the ranges are 421.7–488.1 and 350.9–367.3 μ rad 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 "spatial 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 made to the grating design that drastically reduce this effect. Analysis of the 25 microlamp target data allows verification that the spatial shift on the VIS channel reaches about 2 spatial pixels between the two spectral extremes of the range (255 nm and 1071 nm). 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 associated 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

The 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 μ m 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 μ m 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 section 5, 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 of 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 (a 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 absolute value of the radiance has been tested in flight during dedicated observations of known targets, such as stars (Arcturus and Canopus) and planets (Mars). 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 $t_i = 10$ s. The Responsivity, R, is therefore calculated by applying the following equation:

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

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 by 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 evaluated for a given blackbody temperature and integration time: 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. Therefore, the responsivity is retrieved by using only the signal intervals as indicated in following:

TBB (°C)	t_i (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
100	1.0	148	239
	2.0	140	195
	5.0	120	170
	200	0.2	110
200	1.0	80	120
	2.0	70	105
	5.0	65	95
	300	0.2	60

	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 were checked during in-flight conditions by using internal calibration sequences. 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 instrument 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, consists of the acquisition of a sequence of 35 frames organized into the following steps: 5 acquisitions of electronic offsets, 5 acquisitions of background signal, 5 acquisitions of dark currents, 5 acquisitions of the IR lamp signal, 5 acquisitions of the VIS lamp signal, 5 more acquisitions of dark currents and finally 5 acquisitions of background signal.

The electronic offset is measured by acquiring 5 frames with both detectors on with an exposure time of zero seconds, while maintaining the instrument cover closed and the shutter open, so to read only the "electronic noise produced inside" the instrument chassis, isolated from any signal coming from outside.

The background signal is instead measured by acquiring 5 frames in the same condition defined for the electronic offset, except for setting an exposure time greater than zero for both detectors.

The dark current frames are produced while keeping both the shutter and the cover closed and activating both detectors.

The measurements of the dark currents and that of the background signal are repeated twice during calibration mode, to record their values both before and after the activation of the internal calibration lamps. Finally, the signal from the calibration lamps is measured by activating the given calibration lamp (IR or VIS), with the shutter open and the cover closed with the internal side illuminated by the lamp itself.

Calibration is done illuminating with one lamp at a time.

In the following table these different phases are listed.

Phase	Frames Number	Cover	Shutter	IR lamp	VIS lamp	Exp. Time VIS(s)	Exp Time IR(s)
Electronic Offset	1-5	closed	open	off	off	0.0	0.0
Background 1	6-10	closed	open	off	off	1.0	0.5
Dark Current 1	11-15	closed	closed	off	off	1.0	0.5
IR Lamp	16-20	closed	open	on	off	20.0	0.5
VIS Lamp	21-25	closed	open	off	on	1.0	0.02
Dark Current 2	26-30	closed	closed	off	off	1.0	0.5

Background 2	31-35	closed	open	off	off	5.0	5.0
--------------	-------	--------	------	-----	-----	-----	-----

[INTERNAL CALIBRATION SEQUENCE]

Data acquired during this sequence are fundamental to follow the temporal evolution of the instrument and to monitor the overall performances in operative conditions. They can also be used in the calibration pipeline.

8. CALIBRATION REFINEMENT

During the mission operations at Vesta, we identified some artifacts in the instrumental transfer function (ITF) in the 2.5–3.5 μm spectral range, where several absorption bands of OH and H₂O occur. These artifacts are systematic **and of the same relative magnitude in all images**, and therefore they do not prevent the detection of relative spectral variations associated with OH and H₂O on the surfaces of the target bodies. These artifacts are systematic errors due to the non-homogenous instrumental response of a detector producing nonphysical spectral signatures. The precise cause of the artifacts are not yet fully understood, but involve separately or in combination imperfect radiance calibration, spectral miscalibration, peculiar readout noise in the detector electronics, and from uncertainties in the solar reference spectrum. Nevertheless, we have devised a means to correct the ITF using the onboard lamps.

To compute the ITF for this range, we used in-flight data from one of the internal lamps of the spectrometer. This lamp, made of a tungsten filament, is characterized by a blackbody-like emission at about 2400 K. Since the spectrum of the infrared radiation emitted by these filaments is featureless, a polystyrene filter was inserted for a wavelength calibration of the IR channel. The blackbody radiation of the internal lamp has been used to retrieve a relative ITF in the 2.5–3.5 μm spectral range. First, we calibrated the signal from the internal calibration lamp with the on-ground response function, and then we retrieved the equivalent temperature of the radiation fitting a Planck curve, a value around 1500 Kelvin. The new ITF is the result of the ratio between the raw signal of the lamp and the Planck function. This ratio must be multiplied by a factor to take into account the integration time used to acquire the signal, the transmittance of the polystyrene filter, and the viewing geometry. We compared the ITF obtained with the on-ground calibration with the in-flight calibration and a combination of the two, and we analyzed the calibrated spectra computed with these three versions of the ITF: the comparison graphs between these three curves can be found in [8]. We observe that the new ITF minimizes most calibration residuals that were showing as artifact peaks between 2.5 and 2.9 μm in the previous calibration. The final ITF (version 2) is the ITF derived during the on-ground calibration campaign with the exception of the spectral channels between 2.5 and 3.5 μm where the ITF is derived using the method described here.

9. 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 proprietary GSE (Ground Support Equipment) and converted into standard PDS (Planetary Data System) format. Dedicated package scripts and routines and calibration files distributed with this archive are used to convert the raw data in physical units.

Only for the visible channel, a specific detilt algorithm must be applied to the raw cube to deal with the spatial shift described in chapter 4. This algorithm is applied as a first step in the calibration procedure, before any other step described in this section.

The spatial tilt effect in the visible channel can be compensated by a shift of equal magnitude directed towards the opposite axis of the sample.

The detilting is obtained through the following steps:

- resampling the signal of each frame on a matrix expanded by a factor 40 along the slit axis (corresponding to 20 times the tilt value measured during the calibration on the ground, which is 2 samples);
- shift of the signal in all the spectral channels;
- resampling the corrected frame signal to the original size of 432 × 256 pixels

The value 20 as a multiplicative factor, has been chosen to find a suitable compromise between the accuracy of the algorithm and the computational time required to obtain the result.

The spatial offset applied is a constant value of 2 samples along the slit. As a result, the frame obtained has the same size of the original frame, but the two ending columns (corresponding to two samples) are filled with empty values and are unusable.

The routine implementing the steps above is shown in the following IDL code snippet: the input data for this routine is the raw cube (`raw_qube`), while the output data is the detilted raw qube(`raw_qube_detilt`).

```
frame_expanded=uintarr(bands,samples * 44)

frame_exp_detilt=uintarr(bands,samples * 40)

raw_qube_detilt=uintarr(bands,samples,lines)

; number of pixel by which each sample in each spectral channel has to be shifted
for li=0,lines-1 do begin
    ; step 1: oversampling

    for sa=0,samples-1 do begin

        for ss=0,39 do begin

            frame_expanded(*,sa*40+ss)=reform(raw_qube(*,sa,li))

        endfor

    endfor

endifor

; step2: detilt

for sa=0,samples-1 do begin

    for ba=0,bands-1 do begin

        bsh=ba/4

        for ss=0,39 do begin

            frame_exp_detilt(ba,sa*39+ss)=frame_expanded(ba,sa*39+ss+bsh)

        endfor

    endfor

endifor

endifor

; step3: resampling to the original size
```

```

for sa=0,samples-1 do begin
    tot=dblarr(bands)
    for ba=0,bands-1 do begin
        for ss=0,39 do begin
            tot(ba)=frame_exp_detilt(ba,sa*40+ss)+tot(ba)
        endfor
        raw_cube_detilt(ba,sa,li)=tot(ba)/40.0
    endfor
endfor
endfor

```

The Software Interface Specification (SIS) document contains the details of VIR data cube format and processing steps, detailed briefly here. 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 in 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 consecutively acquired dark frames. The dark subtracted frames are computed subtracting the equivalent dark current frame from 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 into physical units of spectral radiance Rad ($W m^{-2} \mu m^{-1} sterad^{-1}$) by using the following equation:

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

where:

- $S(\lambda(b),s,l)$ 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;

- $\lambda(b)$ 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;

- $ITF(\lambda(b), s)$ 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 (sometimes termed 'I/F'), the equation is:

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

where

-R($\lambda(b)$, s, l) is the cube calibrated reflectance factor which has the same number of bands and samples as 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_Vx.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_Vx.DAT, 432x256 floating precision matrix containing the VIR-IR Instrumental Transfer Function, including the IR flat-Field.

- DAWN_VIR_VIS_HIGHRES_SPECAL_Vx.TAB and

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

- DAWN_VIR_VIS_WIDTH432_Vx.TAB and

- DAWN_VIR_IR_WIDTH432_Vx.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_Vx.TAB and

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

- DAWN_VIR_VIS_WIDTH144_Vx.TAB and

- DAWN_VIR_IR_WIDTH144_Vx.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 are calibrated by using this basic pipeline. Further improvements, based on the use of the internal calibration sequences, may be included in future data releases. The ITF is also currently under improvement. Calibrated values in the spectral range [2.818 μ m - 3.272 μ m] are still under

verification. These values have been put to null in the ITF only for the acquisitions performed during the mission campaigns VSH and VH2; during these two campaigns, a major external contamination is taken as responsible for the artifacts affecting the spectral range around 3 micrometers. The effects of the contamination on this spectral range have been avoided for acquisitions performed after these campaigns. This result was obtained by commanding the instrument into a given operative mode characterized during the analysis of this phenomenon. Such analysis come to the decision of minimizing the duration of the cryo-cooler activity, switching it off whenever compatible with the planned observation. Specifically, the cryo-cooler was always turned off at the end of each observation sequence. The team is also preparing a specific algorithm to apply a correction for these two campaigns that will be released in the future.

10. KNOWN INSTRUMENT ARTIFACTS

VIR spectra are affected by residual systematic errors due to imperfect radiometric and spectral calibration that influence the quality of imaging spectrometer data. These include systematic deviations from spectrum of the target due to imperfect radiometric standards, by spectral miscalibration, and by systematic errors resulting from uncertainties in the solar reference spectrum.

The spectral images can show 'stripes' due to the slight deviation that exists between the input/output transfer function of each sample of the detector. These stripes are particularly evident when the signal is very low.

Visible channels with a wavelength > 0.95 microns cannot be used for scientific analysis, because of the straylight effect which currently has no correction. By excluding these wavelengths from the spectrum, the offset between the visible and the infrared channels in the range where they meet disappears. In some sporadic cases where this offset can still be observed, the instrument team recommends scaling the IR channel to the VIS channel, as the latter is in a good agreement with the Framing Camera dataset.

Defective pixel and filters boundaries should be not considered for any scientific analysis. The filter boundaries and defective pixels are listed in the tables below. Bands contiguous to the filter boundaries may be affected by straylight: the presence and intensity of straylight depends on the specific conditions at which each spectrum has been acquired. Therefore, the user shall check the presence of this effect and eventually discard the bands affected.

A discontinuity in the band pass filters between filters 3 and 4 results in a discontinuity in the transmissivity near 2.4 microns. When the data are corrected for variations in transmissivity a spike is introduced at this discontinuity (see fig. 8b in [3]).

VIR spectra are affected by a positive slope in the VIS-NIR range when compared to ground based spectra of the same target (Vesta and Ceres). Although the origin of this effect is not currently understood, we decided to re-normalize the VIR dataset to correct this effect. The correction is a scale factor computed as the ratio between a ground based reference and VIR spectrum of Ceres. For further details see [8].

The instrument team is working to resolve some of the issues described here. The team plans to release, in the near future, a new level of derived data products that will partially solve the problems above reported. The 'artifact removed' data set is planned for future release.

Dropouts that may be observed in some images are due to instrument saturation. The spectral range in which these dropouts occur varies depending upon exposure duration, target topography, and incidence angle.

In the following table, the filter boundaries positions are listed.

CHANNEL	SAMPLE INTERVAL	BAND INTERVAL	WAVELENGTH INTERVAL (nm)
VIS	1 - 256	222-223	673.30398 - 675.19621
IR	1 - 256	49 - 54	1474.79668 - 1522.09328

IR	1 - 256	156 - 161	2486.94392 - 2534.24052
IR	1 - 256	290 - 293	3754.4928 - 3782.87076
IR	1 - 256	357-360	4388.26724 - 4416.6452

[VIR DETECTOR FILTERS BOUNDARIES]

The defective pixels are listed below.

CHANNEL	SAMPLE	BAND INTERVAL	WAVELENGTH INTERVAL (nm)
VIS	30	308	836.03576
VIS	31	308	836.03576
VIS	47	409	1027.15099
VIS	48	187-188	607.07593-608.96816
VIS	49	59	364.87049
VIS	54	137	512.46443
VIS	71	215	660.05837
VIS	100	78	400.82286
VIS	108	413	1034.71991
VIS	109	19	289.18129
VIS	111	19	289.18129
VIS	114	424	1055.53444
VIS	118	363	940.10841
VIS	126	410	1029.04322
VIS	130	292	805.76008
VIS	136	271	766.02325
VIS	139	235	697.90297
VIS	147	222	673.30398
VIS	150	54	355.40934
VIS	150	59	364.87049
VIS	150	78	400.82286
VIS	160	372	957.13848
VIS	162	36-37	321.3492-323.24143
VIS	162	248	722.50196
VIS	162	330	877.66482
VIS	163	36-37	321.3492-323.24143
VIS	163	248	722.50196
VIS	163	330	877.66482
VIS	165	32	313.78028
VIS	166	32	313.78028
VIS	166	173	580.58471
VIS	168	232	692.22628
VIS	169	363	940.10841
VIS	172	189	610.86039
VIS	173	92	427.31408
VIS	175	228	684.65736
VIS	175	266-267	756.5621-758.45433
VIS	176	152	540.84788

VIS	176	229	686.54959
VIS	177	155	546.52457
VIS	179	196	624.106
VIS	181	249	724.39419
VIS	183	354	923.07834
VIS	186	238	703.57966
VIS	186	387	985.52193
VIS	188	276	775.4844
VIS	188	352	919.29388
VIS	189	294	809.54454
VIS	189	352	919.29388
VIS	189	391	993.09085
VIS	189	413	1034.71991
VIS	190	195	622.21377
VIS	191	411	1030.93545
VIS	194	358	930.64726
VIS	196	266	756.5621
VIS	196	362	938.21618
VIS	199	23-24	296.75021-298.64244
VIS	203	257	739.53203
VIS	203	370	953.35402
VIS	204	257	739.53203
VIS	207	265	754.66987
VIS	211	291	803.86785
VIS	216	287	796.29893
VIS	222	249	724.39419
VIS	222	338	892.80266
VIS	223	339-340	894.69489-896.58712
VIS	225	274	771.69994
VIS	227	103	448.12861
VIS	229	248	722.50196
VIS	234	306	832.2513
VIS	234	424	1055.53444
VIS	238	249	724.39419
VIS	238	277	777.37663
VIS	238	416-417	1040.3966-1042.28883
VIS	239	405	1019.58207
VIS	241	15-16	281.61237-283.5046
VIS	241	386-387	983.6297-985.52193
VIS	242	15-16	281.61237-283.5046
VIS	242	364	942.00064
VIS	245	128	495.43436
VIS	248	304-305	828.46684-830.35907
VIS	250	223	675.19621
VIS	251	223	675.19621

VIS	252	274	771.69994
VIS	253	307	834.14353
IR	8	86	1824.79152
IR	12	148	2411.26936
IR	16	327	4104.48764
IR	20	39-43	1380.20348-1418.04076
IR	21	39-42	1380.20348-1408.58144
IR	22	40-42	1389.6628-1408.58144
IR	27	374	4549.07568
IR	35	218	3073.42176
IR	45	337	4199.08084
IR	51	212	3016.66584
IR	52	280	3659.8996
IR	56	430	5078.7976
IR	74	121	2155.86772
IR	79	185	2761.2642
IR	79	190	2808.5608
IR	82	190	2808.5608
IR	84	188	2789.64216
IR	86	182	2732.88624
IR	86	200	2903.154
IR	92	30	1295.0696
IR	94	189	2799.10148
IR	99	73	1701.82036
IR	100	73	1701.82036
IR	101	223-224	3120.71836-3130.17768
IR	102	72	1692.36104
IR	102	223	3120.71836
IR	102	225	3139.637
IR	103	223	3120.71836
IR	111	304	3886.92328
IR	112	28	1276.15096
IR	121	193	2836.93876
IR	122	172	2638.29304
IR	128	149	2420.72868
IR	128	187	2780.18284
IR	130	195	2855.8574
IR	132	182	2732.88624
IR	136	344	4265.29608
IR	138	383-384	4634.20956-4643.66888
IR	140	202	2922.07264
IR	142	341-342	4236.91812-4246.37744
IR	143	343	4255.83676
IR	144	343	4255.83676
IR	145	343	4255.83676

IR	146	342	4246.37744
IR	146	344	4265.29608
IR	148	108	2032.89656
IR	149	169-170	2609.91508-2619.3744
IR	155	1	1020.74932
IR	156	1-9	1020.74932-1096.42388
IR	156	196	2865.31672
IR	157	1-15	1020.74932-1153.1798
IR	157	25	1247.773
IR	158	9-17	1096.42388-1172.09844
IR	159	14-18	1143.72048-1181.55776
IR	160	19-20	1191.01708-1200.4764
IR	160	28-29	1276.15096-1285.61028
IR	161	26	1257.23232
IR	161	28-29	1276.15096-1285.61028
IR	161	181	2723.42692
IR	171	57-64	1550.47124-1616.68648
IR	172	57-64	1550.47124-1616.68648
IR	172	227	3158.55564
IR	173	59-68	1569.38988-1654.52376
IR	174	60-67	1578.8492-1645.06444
IR	175	61-63	1588.30852-1607.22716
IR	191	111-112	2061.27452-2070.73384
IR	192	110-113	2051.8152-2080.19316
IR	193	111-112	2061.27452-2070.73384
IR	193	245-246	3328.8234-3338.28272
IR	219	428	5059.87896
IR	227	211	3007.20652
IR	228	79	1758.57628
IR	228	222	3111.25904
IR	229	116	2108.57112
IR	234	175	2666.671
IR	235	175	2666.671
IR	235	226	3149.09632
IR	236	186	2770.72352
IR	237	129	2231.54228
IR	238	38	1370.74416
IR	241	233	3215.31156
IR	243	202	2922.07264
IR	244	228	3168.01496
IR	245	191-192	2818.02012-2827.47944
IR	250	414	4927.44848

[VIR DETECTOR DEFECTIVE PIXELS]

Note that for the VIS detector, pixels located at these coordinates are to be considered both as filter boundaries and defective:

- sample 147, band 222

- sample 250, band 223
- sample 251, band 223

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