

Imaging Surveys at the VLT Survey Telescope Data Release 2 (DR2)

Abstract

The VLT Survey Telescope (VST) is a 2.6-m optical wide-field telescope installed at the ESO observatory of Cerro Paranal (Chile). The only instrument at the VST is OmegaCAM, which is a wide-field camera, covering 1 square degree in the sky, with 0.21 arcsec per pixel. On 1st October 2022, after more than 10 years of activity, the INAF-ESO contract expired and the VST became a hosted telescope at ESO. VST is currently owned and managed by INAF, and a new 5-year, 2022-2027 (renewable) INAF-ESO agreement was signed to define rules and roles.

Since then, the INAF-Coordination Centre for the VST is in charge of managing the operations at the VST.

The VLT Survey Telescope (VST) has been one of the most efficient wide-field imagers in the optical bands since the start of operations in 2011.

The VST has played a pivotal role in expanding our understanding of the universe. By surveying the night sky with unparalleled precision, this telescope has provided astronomers with a wealth of data on a diverse range of astronomical phenomena, from distant galaxies and clusters to galactic objects.

In the following sections, we describe a collection of imaging data obtained using VST, detailing the use of different specific filters to enhance observational capabilities.

The dataset, gathered using high-resolution imaging techniques, spans a wide range of celestial objects, from distant galaxies' clusters to nearby galaxies and star clusters. The observations have been conducted by using almost all the VST filters, e.g. u, g, r, i, z, H_α , allowing for precise photometric measurements and detailed color analyses of the captured objects, enhancing the dataset's utility for researchers exploring various astrophysical phenomena. This release also includes some data taken before the new INAF-ESO agreement.

This VST imaging data collection, with its extensive filter coverage, stands as a valuable asset for observational astronomers, enabling in-depth studies of the universe's structures and characteristics.

We plan to release new reduced data twice a year. New survey projects will be added, along with additional data to the already released ones.

Overview of Observations

The data released belong to the survey projects explained in detail below. Targets, covered area, filters, and total exposure times of the data in this collection are listed in Table 1.

- 1) The "Pre-supernova outbursts in Galactic Red Supergiants: predicting the next Galactic SN event (GALRSG, P.I. F. Bocchino)" is a monitoring program aimed at characterizing the multi-color light curves of a coeval and co-distant sample of RSGs in the Scutum-Crux region (see Figure 2), to detect late-stage outbursts and to compare them with the very recent models of the final phases of low-mass RSGs before SN explosion, thus possibly predicting core collapse before it occurs. This program carries out dedicated monitoring of the RSG catalog in the i and z bands of a large highly absorbed area of the galactic plane with a cadence of a few days, and it will likely remain a very good choice also in the LSST era.
The data have been processed with the Astro-WISE data reduction pipeline. Data from this survey can be selected via the header keyword "SUR_REG = GALRSG" and/or via "PROG_ID" header keywords, where the PROG_ID is the following: 113.26YN.001.

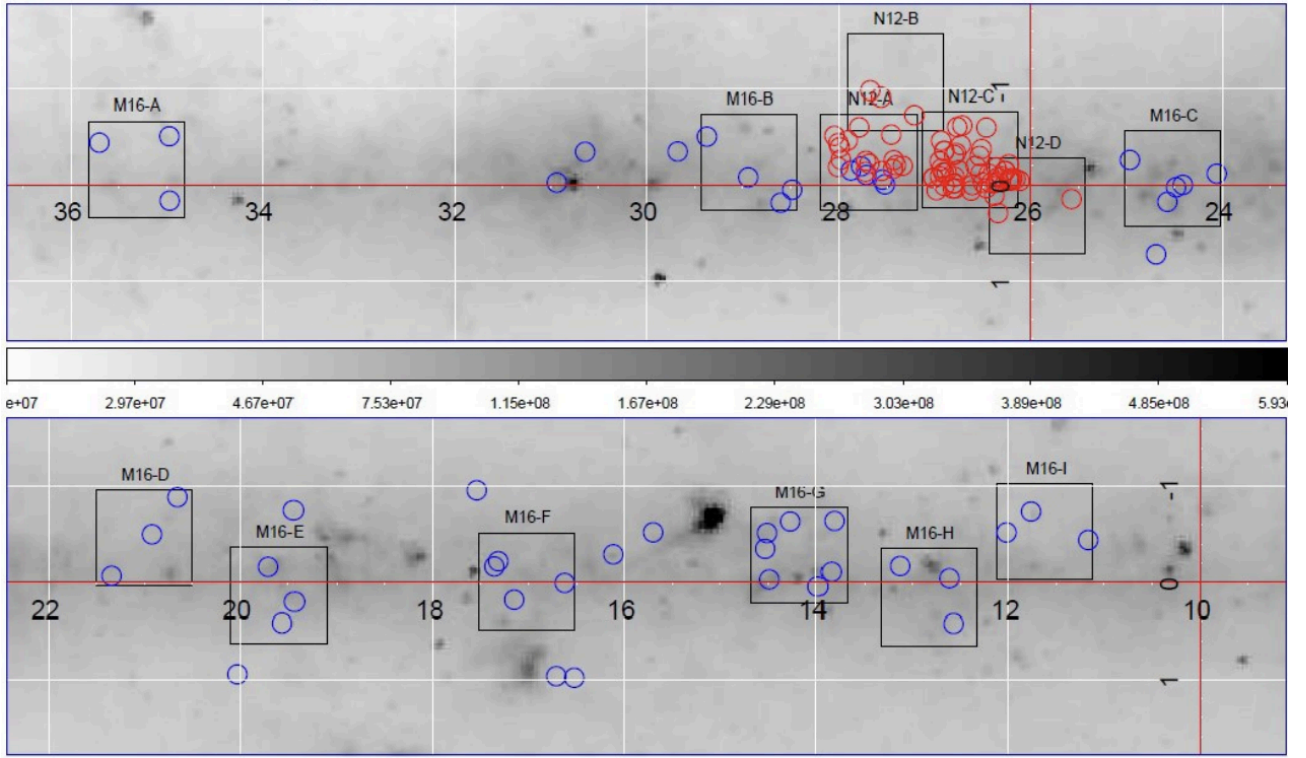


Figure 1: Top panel: A grey-scale image of the 12 μm band emission of the Galactic plane in the range $23^\circ < l < 37^\circ$ and $-1.5^\circ < b < 1.5^\circ$ as observed by IRAS, on which have been overimposed the sources of Neguerela+ (2012, N12, red circles) and of Messineo+ (2016, M16, blue circles) selected for this monitoring campaign. Black boxes are $1^\circ \times 1^\circ$ VST OmegaCAM pointings of the campaign. The location of the pointings has been chosen to have at least 3 sources from the proposed list in the OmegaCAM FOV and to maximize the coverage of the set. Bottom panel: Same as the top panel, but for $10^\circ < l < 22^\circ$.

- 2) The “VST Survey of Mass Assembly and Structural Hierarchy” (VST-SMASH, P.I. C. Tortora) is a Large Program using the VST to conduct a definitive deep imaging census of faint tidal remnants (streams and shells) around 27 nearby galaxies ($D < 11$ Mpc) in the Southern Sky, with the goal of constraining the hierarchical assembly process via minor mergers. To achieve the requisite depth, reaching $\mu \geq 29$ mag arcsec $^{-2}$ in g and r bands and $\mu \geq 26$ mag arcsec $^{-2}$ in i, over roughly 220 hours, the program employs an essential ON-OFF dithering strategy: for each galaxy (the ‘ON’ science field), a second adjacent field (the ‘OFF’ sky frame) is observed immediately after. This adjacent field is used to accurately model and subtract the highly variable sky background - a critical step to prevent the faint LSB features from being erroneously removed as mere sky fluctuations by the data reduction pipeline. This approach ensures the successful detection and characterization of the elusive stellar structures, providing legacy data for comparison with cosmological simulations and complementing future Euclid and LSST observations. In this collection are released the g, r, and i band images of the galaxies NGC3109 and Sextans A. The data have been processed with the Astro-WISE data-reduction pipeline. Data from this survey can be selected via the header keyword “SUR_REG = VST-SMASH” and/or via “PROG_ID” header keywords, where the PROG_ID is the following: 110.25AA.001.

Targets, covered area, filters, and total exposure times of the data in this collection are listed in Table 1. In this table, the adopted observing strategy for each target is also included. The various data reduction pipelines utilized are described in the following sections.

Release Content

Target (1)	RA [h m s] (2)	Dec [d m s] (3)	u' [sec] (4)	g' [sec] (5)	r' [sec] (6)	i' [sec] (7)	z' [sec] (8)	Area [deg ²] (9)	Strate gy (10)	Prog. (11)
M16-A	18:56:23.1	+02:02:49	-	-	-	4950	4950	1	Standard	GALRSG
M16-B	18:44:58.0	-03:39:53	-	-	-	4230	4200	1	Standard	GALRSG
M16-D	18:31:06.4	-07:30:52	-	-	-	4200	4200	1	Standard	GALRSG
M16-E	18:26:17.2	-10:49:09	-	-	-	4470	4350	1	Standard	GALRSG
N12-A	18:42:40.6	-04:46:36	-	-	-	4500	4500	1	Standard	GALRSG
N12-B	18:45:09.8	-05:23:40	-	-	-	4770	4530	1	Standard	GALRSG
N12-C	18:40:51.9	-05:43:31	-	-	-	4350	4350	1	Standard	GALRSG
N12-D	18:37:50.9	-06:07:34	-	-	-	4470	4350	1	Standard	GALRSG
NGC 3109	10:03:09.7	-26:22:18	-	19800	57240	16200	-	1	Step dither	VST- SMASH
Sextans A	10:00:36.4	05:08:45	-	10800	10800	9000	-	1	Step dither	VST- SMASH

Table 1. Target list of this release. In column 1 is given the target name. In columns 2 and 3 are listed the J2000 celestial coordinates. From columns 4 to 8 are reported the total integration time for each 1 square deg field, in the u', g', r', i', and z' bands, respectively. In column 9 is indicated the total covered area of the mosaic. In columns 10 and 11 are indicated the adopted observing strategy and the project associated with the data.

Release Notes

Data Reduction and Calibration

The data belonging to this release have been reduced using the same software; the information can be found in the file header under the keyword PROCESOFT. An overview of the pipeline used is provided below.

Astro-WISE

The data released in this collection have been reduced by using the Astronomical Wide-field Imaging System for Europe (Astro-WISE) pipeline (McFarland et al. 2013), also used for the KIDS survey. The instrumental corrections applied for each frame include overscan correction, removal of bias, flat-fielding, illumination correction, masking of the bad pixels, and subtraction of the background.

- **De-biasing and overscan correction.** The data is overscan corrected by subtracting from each pixel row the row-wise median values, read from the CCD overscan areas. The fine structure of the bias is then subtracted using a master bias frame stacked from ten overscan corrected bias frames.
- **Flat-fielding.** Flatfielding is done after bias correction using a master flat-field which is combined from twilight flatfields and dome flatfields. Before combining the different flat-fields, the high spatial

frequencies are filtered out from the twilight flat-fields, and the low frequency spatial Fourier frequencies from the dome flat-fields.

- **Weight maps.** During the instrumental reduction, weight maps are also created for each individual frame. Weight maps carry information about the defects or contaminated pixels in the images and also the expected noise associated with each pixel. The hot and cold pixels are detected from the bias and flatfield images, respectively. These pixels are then set to zero in the weight maps. The flatfielded and debiased images are also searched for satellite tracks and cosmic rays, and the values of the pixels in the weight maps corresponding to the contaminated pixels in the science images, are then set to zero.
- **Illumination correction.** Systematic photometric residual patterns still remain after flat-fielding, which are corrected by applying an illumination correction to the data. The correction models are made by mapping the photometric residuals across the OmegaCAM's CCD array using a set of dithered observations of Landolt's Selected Area (SA) standard star fields (A.U. Landolt, 1992, AJ, 104, 340), and fitting a linear model to the residuals. The images were multiplied with this illumination correction. The illumination correction is applied after the background removal to avoid producing artificial patterns in the background of images.
- **De-fringing.** De-fringing is only needed for i-band. Analysis of nightly fringe frames showed that the pattern is constant in time. For each science exposure, this fringe image is scaled (after background subtraction of the science exposure and fringe frame) and then subtracted to minimize residual fringes.
- **Astrometric calibration.** The first-order astrometric calibration was done by first matching the pixel coordinates to RA and Dec using the World Coordinate System (WCS) information from the fits header. Point source coordinates were then extracted using SExtractor and associated with the 2 Micron All Sky Survey Point Source Catalog (2MASS PSC, Skrutskie et al. 2006). The transformation was then extended by a second-order two-dimensional polynomial across the focal plane. SCAMP (Bertin 2006) was used for this purpose. The polynomial was fitted iteratively five times, each time clipping the 2σ -outliers. The astrometric solution gives typically rms errors of 0.3 arcsec (compared to 2MASS PSC) for a single exposure, and 0.1 arcsec for the stacked final mosaic.
- **Photometric calibration.** The absolute photometric calibration was performed by observing standard star fields each night and comparing their OmegaCAM magnitudes with the Sloan Digital Sky Survey Data Release 11 (SDSS DR11, Alam et al. 2015) catalog values. The OmegaCAM point source magnitudes were first corrected for the atmospheric extinction by subtracting a term kX , where X is airmass and k is the atmospheric extinction coefficient with the values of 0.182, 0.102 and 0.046 for g' , r' and i' , respectively. The zero-point for a given CCD is the difference between the object's corrected magnitude measured from a standard star field exposure and the catalog value. The zero-point for each CCD was kept constant for the whole night, only correcting for the varying airmass.
- **Background subtraction.** For images observed with the step-dither strategy, a background model is created first by scaling a set of 12 consecutive exposures of the targets, and then median averaging the stack. The scaling factors between images A and B is defined by measuring median values within small boxes in image A (m_A), and in the same locations in image B (m_B), and then taking the median of their ratios: $s = \text{median}(m_A/m_B)$. For each image among those to be stacked, such a scaling factor is defined with respect to A, and the images are multiplied with these factors before stacking. If there is a large scatter between the ratios of s , the chip medians of the exposures are scaled with each other. The scaled images are then median stacked to the background model, and the model is subtracted from image A.
- **Regriidding and coadding.** After the astrometric and photometric calibrations, the images were sampled to 0.20 arcsec pixel size and combined using the SWarp software (Bertin 2010). Before combining the images, cosmic rays and bad pixels were removed using the weight maps.

Photometric zero point. In the Astro-WISE pipeline, the zero point is applied directly to the image during the photometric calibration. As a result, if the header keyword PHOTZP = 0.0, this indicates that the image fluxes are already calibrated in physical units, and no further zero-point adjustment is needed. If a non-zero PHOTZP value appears, it typically indicates that the image was pre-reduced with Astro-WISE, but additional in-house processing (e.g., coaddition or stacking) was applied afterward.

Data Quality

In Table 2 we report the limiting magnitudes and the average FWHM within the field for each set of observations and in the different photometric bands. Same information is also reported in the image header (under PSF_FWHM and ABMAGLIM keywords). The limiting magnitude is the surface brightness of a point source corresponding at 5σ of the background noise in the image. The RMS error of the astrometric solution is ~ 0.3 arcsec.

Target (1)	FWHM [arcsec]					Depth [mag]				
	u' (2)	g' (3)	r' (4)	i' (5)	z' (6)	u' (7)	g' (8)	r' (9)	i' (10)	z' (11)
M16-A	-	-	-	0.7	0.72	-	-	-	23.82	22.86
M16-B	-	-	-	0.75	0.77	-	-	-	22.79	21.95
M16-D	-	-	-	0.73	0.72	-	-	-	22.85	21.87
M16-E	-	-	-	0.71	0.76	-	-	-	22.37	21.48
N12-A	-	-	-	0.82	0.86	-	-	-	22.00	21.22
N12-B	-	-	-	0.72	0.72	-	-	-	20.98	20.43
N12-C	-	-	-	0.77	0.77	-	-	-	21.58	20.84
N12-D	-	-	-	0.80	0.84	-	-	-	22.90	22.03
NGC3109	-	0.52	0.64	0.94	-	-	25.78	25.35	24.42	-
Sextans A	-	0.63	0.76	0.52	-	-	25.66	24.77	24.48	-

Table 2. Data quality of data in this release. In column 1 is given the target name. From columns 2 to 6 are reported the average FWHM seeing, in the u' , g' , r' , i' , and z' bands, respectively. From columns 7 to 11 are reported the limiting magnitude for a point-source computed at 5σ of the background level, in the u' , g' , r' , i' , and z' bands, respectively.

Data Format

Files Types

The files are in FITS format, with the relevant information in the header. They have been compressed using NASA's HEASARC's fpack routine (<https://heasarc.gsfc.nasa.gov/fitsio/fpack/>). Each science frame is accompanied by a weight frame. Files are named based on the field covered and the filter used for observations, following the format:

<TargetName>_<FilterName>_sci.fits.fz for science images and
 <TargetName>_<FilterName>_wei.fits.fz for weight maps.

The programme **GALRSG**, which is a cadence programme, will also include the **<DATE>** in the filenames to indicate the observing epoch. Accordingly, the new filenames are:

<TargetName>_<FilterName>_<DATE>_sci.fits.fz for science images and
 <TargetName>_<FilterName>_<DATE>_wei.fits.fz for weight map

Acknowledgements

According to the Data Access Policy for ESO data held in the ESO Science Archive Facility, all users are required to acknowledge the source of the data with appropriate citation in their publications.

Since processed data downloaded from the ESO Archive are assigned Digital Object Identifiers (DOIs), the following statement must be included in all publications making use of them:

- *Based on data obtained from the ESO Science Archive Facility with DOI:
<https://doi.eso.org/10.18727/archive/98>*
- *Based on data collected with the INAF VST telescope at the ESO Paranal Observatory*

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- *Based on data obtained from the ESO Science Archive Facility under request number
<request_number>.*

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