Imaging Surveys at the VLT Survey Telescope Data Release 3 (DR3)

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,Hα*, 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. The various data reduction pipelines utilized are described in the following sections.

1) The "Stellar Explosions and their Evolution In Nearby Galaxies (SEEING, P.I. L. Izzo) with the VST" aims at detecting classical novae in nearby galaxies with the goal to determine their explosion rate, a fundamental ingredient for the role of novae in chemical evolution studies, and as a proxy for their progenitors' stellar populations. Moreover, the cadence used will also allow us to discover and follow up intermediate-luminosity transients such as luminous blue variables and red novae, in addition to hunting for progenitor stars of direct collapse black holes. The final multi-filter stacked mosaics, obtained from the entire set of images of every single galaxy, will be useful as an atlas for detailed stellar population studies, to search for low-surface brightness satellites and as a template for higher redshift transients, exploding in the background galaxies. The methodology developed in this two-year program is already serving as a training preparatory work for future studies available with the incoming Vera Rubin telescope.

The goal of the project consists in measuring the properties of classical novae (CNe) in very nearby galaxies (e.g. d < 7 Mpc) using VST detections and follow-up of newly discovered events. The galaxy sample has been selected in order to maximize its coverage in both g and r bands.
The data have been processed with the VST pipeline. Data from this survey can be selected via the header keyword "SUR_REG = SEEING" and/or via "PROG_ID" header keywords, where the PROG_ID is the following: 112.266U.001

2) The project "Search for SN explosions from Pop III "analogs" in the Local Universe (SN, P.I. M. Della Valle)" aims to use VST to search for "Pop III SN-like" events in the relatively nearby Universe (z < 1). These objects should be detected as super luminous supernovae, characterized by long-lasting maxima, produced
in the explosions of pair instability supernovae occurring in progenitor stars with masses > 100 Msun. This program carried out in the nearby universe is designed to prepare future research/observations of "genuine" Pop III supernovae which will be carried on with LSST and JWST. Targets have been selected considering several constraints, such as the extragalactic field, including also cluster lenses (which would allow us to search also for high-redshift lensed supernovae) and deep fields such as the COSMOS and the HDF South, and observed in g and r bands.
The data have been processed with the VST pipeline. Data from this survey can be selected via the header keyword "SUR_REG = SN" and/or via "PROG_ID" header keywords, where the PROG_ID is the following: 112.266S.001.

3) The project HYPERION Medium Area X-ray Serendipitous Survey (HYPER-MAX, P.I. D. De Cicco) is a deep photometric project designed to provide uniform optical counterparts in the *g, r, i, z* bands for approximately 4,000 X-ray sources detected by the HYPERION XMM-Newton Multi-Year Heritage program. Focusing on 18 non-contiguous fields centered on hyper-luminous quasars from the Reionization Epoch (z>6), the survey covers a total area of approximately 3 square degrees, achieving a sensitivity that surpasses the COSMOS survey for this type of medium-area X-ray study. The primary scientific goal is to overcome the current fragmentation and heterogeneity of multi-wavelength data, enabling a systematic characterization of both distant quasars and thousands of serendipitous X-ray sources, thereby establishing one of the deepest and most homogeneous XMM-VST datasets available for studying Active Galactic Nuclei evolution. The data have been processed with Astro-WISE. Data from this survey can be selected via the header keyword "SUR_REG = HYPER-MAX" and/or via "PROG_ID" header keywords, where the PROG_ID is one of the following: 110.25AE.001, 112.266L.001, 113.26YJ.001. Only a part of the targets in *g, r, i* have been released.

4) The MeerKAT HI Observations of Nearby Galactic Objects: Observing Southern Emitters (MHONGOOSE) project seeks to investigate the fundamental process of gas accretion from the intergalactic medium, which is essential for sustaining star formation in galaxies over cosmic time. By leveraging exceptionally deep neutral hydrogen (HI) observations from the MeerKAT telescope, which have revealed a complex network of gas filaments, streams, and low-surface-brightness dwarf galaxies, the program aims to clarify the origin of these features. To distinguish between pristine gas accretion, galaxy interactions, or dwarf galaxy infalls, the project requires deep, wide-field optical data in the g and r bands from the VST/OmegaCAM. The data have been processed with Astro-WISE. Data from this survey can be selected via the header keyword "SUR_REG = MHONGOOSE" and/or via "PROG_ID" header keywords, where the PROG_IDs are: 110.25AJ.001 (P.I. F. Maccagni), 112.266Y.001 (P.I. A. Marasco), 113.26YW.001 (P.I. D. Kleiner). Only a part of the targets in *g, r* bands have been released.

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)	Strategy (10)	Prog. (11)
J1342	13:42:24.00	+09:11:60.0	-	8100	4200	15550	-	1	standard	HYPER-MAX
J231	15:27:12.00	-21:00:00.0	-	8100	7100	16200	-	1	standard	HYPER-MAX

J0020	00:20:24.00	-36:53:60.0	-	8100	6600	-	-	1	standard	HYPER-MAX
J0038	00:38:48.00	-15:30:00.0	-	-	11220	-	-	1	standard	HYPER-MAX
J0224	02:24:24.00	-47:12:00.0	-	-	9900	-	-	1	standard	HYPER-MAX
J025	01:42:48.00	-33:30:00.0	-	-	9900.402	-	-	1	standard	HYPER-MAX
J0049_20	00:49:48.74	-21:01:03.6	-	-	9000	-	-	1	standard	MHON GOOSE
J0052_31	00:49:48.74	-31:12:21.5	-	9000	9000	-	-	1	standard	MHON GOOSE
J0309_41	-31:12:21.5	-41:01:52.7	-	9000	-	-	-	1	standard	MHON GOOSE
J0310_39	03:10:10.50	-40:00:08.9	-	9000	9000	-	-	1	standard	MHON GOOSE
J0320_52	03:20:07.43	-52:11:09.2	-	-	9000	-	-	1	standard	MHON GOOSE
J0331_51	03:31:31.51	-51:54:18.1	-	9000	9000	-	-	1	standard	MHON GOOSE
J0335_24	03:35:01.37	-24:56:00.8	-	-	10800	-	-	1	standard	MHON GOOSE
J0351_38	03:51:41.20	-38:27:07.4	-	9000	9000	-	-	1	standard	MHON GOOSE
J0429_27	04:29:40.08	04:29:40.08	-	10800	10800	-	-	1	standard	MHON GOOSE
J0445_59	04:45:42.35	-59:14:49.9	-	9300	9000	-	-	1	standard	MHON GOOSE
J0454_53	04:54:13.29	-53:21:40.6	-	-	9000	-	-	1	standard	MHON GOOSE
J0459_26	04:59:57.83	-26:01:22.1	-	9000	9000	-	-	1	standard	MHON GOOSE
J0516_37	05:16:38.74	-37:06:10.0	-	9000	9300	-	-	1	standard	MHON GOOSE
J0546_52	05:46:24.03	-52:05:18.3	-	9000	9000	-	-	1	standard	MHON GOOSE
J2009_61	20:09:31.47	-61:50:56.1	-	9000	9900	-	-	1	standard	MHON GOOSE
J2257_41	22:57:18.52	-41:04:15.9	-	9000	10800	-	-	1	standard	MHON GOOSE
J2357_32	23:57:49.66	-32:35:27.3	-	9000	9000	-	-	1	standard	MHON GOOSE
J1106_14	11:06:11.77	-14:24:23.5	-	9000	9000	-	-	1	standard	MHON GOOSE
J1103_23	11:03:23.84	-23:05:10.0	-	-	9000	-	-	1	standard	MHON GOOSE
J1253_12	12:53:56.58	-12:06:17.7	-	9000	9000	-	-	1	standard	MHON GOOSE

J1303_17b	13:03:13.70	-17:25:02.8	-	9600	-	-	-	1	standard	MHON GOOSE
J1318_21	13:18:54.90	-21:02:19.0	-	9000	9000	-	-	1	standard	MHON GOOSE
J1321_31	13:21:07.93	-31:31:53.0	-	9000	-	-	-	1	standard	MHON GOOSE
J1337_28	13:37:20.13	-28:02:43.4	-	9000	9000	-	-	1	standard	MHON GOOSE
Fornax A	02:40:13.66	-34:35:31.8	-	1800	9000	-	-	1	standard	SEEING
IC 1613	01:05:11.59	+02:03:23.0	-	1800	5400	-	-	1	standard	SEEING
NGC 1291	03:17:40.75	-41:08:00.1	-	3600	9900	-	-	1	standard	SEEING
NGC 1313	03:17:27.72	-66:22:54.5	-	3600	11700	-	-	1	standard	SEEING
NGC 247	00:47:53.43	-20:35:47.8	-	3600	9900	-	-	1	standard	SEEING
NGC 300	00:55:33.89	-37:41:38.8	-	3600	12600	-	-	1	standard	SEEING
NGC 55	00:14:43.08	-39:08:05.3	-	4500	12600	-	-	1	standard	SEEING
NGC 7793	23:57:16.23	-32:38:57.1	-	900	3600	-	-	1	standard	SEEING
Sculptor1	00:59:44.04	-33:53:08.2	-	1800	9900	-	-	1	standard	SEEING
Sex A	10:11:00.46	-04:41:02.9	-	2700	8100	-	-	1	standard	SEEING
Tucana 1	22:42:27.74	-64:27:53.2	-	1800	10800	-	-	1	standard	SEEING
WLM SDSS	00:02:31.31	-15:26:37.8	-	4500	9540	-	-	1	standard	SEEING
MACS-J0416	04:16:08.73	-24:03:48.5	-	6000	6000	-	-	1	standard	SN
MACS-J1931	19:31:51.45	+01:30:28.7	-	1500	1500	-	-	1	standard	SN
SMACSJ0723-gr	07:23:19.75	-73:27:07.3	-	4500	4500	-	-	1	standard	SN

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 PROCSOFT. 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 (mA), and in the same locations in image B (mB), and then taking the median of their ratios: s = median(mA/mB) 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.
- **Regridding 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.

VST pipeline

The VST pipeline is a code entirely written in python (Izzo et al. in preparation). The pipeline utilizes several packages developed for astronomical image analysis, including *astropy* and *ccdproc*, and operates on each individual sensor of the 32 OmegaCam frames.
All calibration and science frames are treated as ''objects'' using the *CCDData* routine available within *ccdproc*. Bias subtraction and flat-field correction of science and standard frames are then applied after calculating the gain and read-out noise from individual bias and flat-field frames. Currently, the pipeline does not perform illumination correction, though this functionality will be implemented soon. Subsequently, all frames are registered to the same spatial grid and photometric scale using *astrometry.net*, which is run locally.

Following registration, single frames from each of the five dithered exposures per epoch are median-averaged and background-subtracted using the *swarp* software, resulting in a stacked image. To refine the plate-solving correction, *scamp* is run on each stacked image. The pipeline also generates a weighted pixel image, which tracks the number of dithered exposures contributing to the combined image, and a mask frame, which accounts for CCD gaps, bad pixels, and cosmic ray rejection, with both images provided as FITS files. Finally, the pipeline was employed to produce deep stacked images by combining all single stacked images for each epoch and in a given filter.

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	**FWHM [arcsec]**					**Depth [mag]**				
(1)	***u′* *(2)***	***g′* *(3)***	***r′* *(4)***	***i′* *(5)***	***z′* *(6)***	***u′* *(7)***	***g′* *(8)***	***r′* *(9)***	***i′* *(10)***	***z′* *(11)***
J1342	-	0.52	0.51	1.13	-	-	26.01	25.18	25.01	-
J231	-	0.44	0.53	1.02	-	-	26.10	25.32	25.06	-
J0020	-	1.04	1.34	-	-	-	26.16	26.20	-	-
J0038	-	-	0.59	-	-	-	-	26.34	-	-
J0224	-	-	1.21	-	-	-	-	26.08	-	-
J025	-	-	1.00	-	-	-	-	26.26	-	-
J0049_20	-	-	0.57	-	-	-	-	25.13	-	-
J0052_31	-	1.07	0.59	-	-	-	26.12	25.32	-	-
J0309_41	-	0.58	-	-	-	-	26.23	-	-	-
J0310_39	-	0.56	1.05	-	-	-	26.12	25.07	-	-
J0320_52	-		1.06	-	-	-	-	25.30	-	-
J0331_51	-	0.57	1.24	-	-	-	26.30	25.14	-	-
J0335_24	-	-	1.22	-	-	-	-	25.26	-	-
J0351_38	-	1.09	1.05	-	-	-	25.59	25.31	-	-
J0429_27	-	1.15	1.02	-	-	-	26.07	25.38	-	-
J0445_59	-	1.06	1.31	-	-	-	25.51	25.06	-	-
J0454_53	-	-	0.55	-	-	-	-	25.50	-	-
J0459_26	-	1.04	1.01	-	-	-	26.27	25.29	-	-
J0516_37	-	1.18	0.59	-	-	-	26.21	25.26	-	-
J0546_52	-	1.01	0.59	-	-	-	26.10	25.09	-	-
J2009_61	-	1.07	1.33	-	-	-	25.47	25.18	-	-

J2257_41	-	1.16	0.47	-	-	-	26.04	25.21	-	-
J2357_32	-	1.07	1.31	-	-	-	26.01	25.38	-	-
J1106_14	-	1.14	1.19	-	-	-	26.34	25.21	-	-
J1103_23	-	-	1.11	-	-	-	-	25.34	-	-
J1253_12	-	1.11	1.08	-	-	-	26.13	25.36	-	-
J1303_17b	-	1.04	-	-	-	-	26.18	-	-	-
J1318_21	-	1.22	1.20	-	-	-	25.50	25.21	-	-
J1321_31	-	1.11	-	-	-	-	26.03	-	-	-
J1337_28	-	1.28	0.55	-	-	-	26.26	25.33	-	-
MACS-J0416	-	1.32	1.31	-	-	-	25.17	25.29	-	-
MACS-J1931	-	1.26	1.42	-	-	-	24.58	24.18	-	-
SMACSJ0723-gr	-	1.09	1.10	-	-	-	25.25	24.53	-	-
Fornax A	-	1.12	1.20	-	-	-	24.24	24.35	-	-
IC 1613	-	1.14	1.06	-	-	-	25.05	24.28	-	-
NGC 1291	-	0.56	1.08	-	-	-	24.52	25.01	-	-
NGC 1313	-	0.54	1.04	-	-	-	24.50	25.06	-	-
NGC 247	-	0.51	1.06	-	-	-	25.08	25.20	-	-
NGC 300	-	0.59	1.08	-	-	-	25.38	25.16	-	-
NGC 55	-	1.09	1.18	-	-	-	25.14	25.25	-	-
NGC 7793	-	0.56	1.03	-	-	-	25.30	25.31	-	-
Sculptor1	-	1.00	1.14	-	-	-	24.54	24.48	-	-
Sex A	-	1.04	1.07	-	-	-	24.57	24.44	-	-
Tucana 1	-	1.09	1.18	-	-	-	25.03	25.22	-	-
WLM SDSS	-	1.33	1.23	-	-	-	25.17	25.30	-	-

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_out.fits.fz for science images and
<TargetName>_<FilterName>_wei_out.fits.fz for weight maps.

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*

Publications making use of data which have been assigned an archive request number (of the form XXXXXX) must include the following statement in a footnote or in the acknowledgement:

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

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