VISTA Science Verification — The Galactic and Extragalactic Mini-surveys

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The Visible and Infrared Survey Telescope for Astronomy (VISTA) will be mostly dedicated to the execution of ESO public surveys, requiring large amounts of service observing time. VISTA Science Verification (SV) thus differs from that usually implemented for other VLT instruments. VISTA SV consisted of two self-contained mini-surveys: a Galactic mini-survey in the region around the Orion Belt stars; and a deep extragalactic mini-survey of the nearby spiral galaxy NGC 253. ESO astronomers used these mini-surveys as benchmarks to optimise the survey operation procedures, minimise overheads, and experience the full end-to-end process of survey data acquisition. The raw data and associated calibrations from both mini-surveys were released in December 2009, and the reduced images and catalogues will soon be available, enabling the first exciting science with VISTA.

Introduction

In the Commissioning–Science Verification–Paranalisation cycle of VLT instruments, Science Verification is typically executed five to two months prior to the start of operations of a given VLT instrument. In the case of VISTA and its camera VIRCAM (Emerson et al., 2004), its start of operation is equivalent to the start of operation of an entire new telescope, a new instrument and a new schema for operations (Sciops 2.0). For ESO service mode operations, the execution of the VISTA public surveys represents a challenge, since they require the definition of several thousands of observing blocks (OBs) that need to be managed, scheduled and executed in the most efficient way. The service mode operations for public surveys use a new version of the Phase 2 Proposal Preparation tool (P2PP) and a new Observing Tool (OT); see Arnaboldi et al. (2008). The creation of OBs for public surveys also requires a new tool called SADT (Survey Area Definition Tool) for the definition of the survey geometry, e.g., filled field positions (or tiles) at a given position on the sky or large areas of several degrees, and the sequence of "pawprint" offsets required for the homogeneous coverage of the VISTA camera focal plane (the 16 detectors in the VIRCAM focal plane are non-contiguous, see Figure 4 of Emerson et al., 2004), and for finding the necessary guide and active optics stars for each pawprint. In addition, VISTA has a different dataflow and quality control (QC) with respect to the other VLT instruments. Finally VISTA and its camera VIRCAM are expected to produce an order of magnitude more data than all the other VLT instruments combined.

The VISTA SV was therefore a fundamental part of the procedure for verification of the end-to-end system for the VISTA telescope + VIRCAM camera + Quality Control + Archive operations. While the individual components could be tested through previous verification and commissioning activities, VISTA SV has enabled ESO to carry out the full test of the integrated system, tools and interfaces across departments, in a "survey-like" operation mode for the first time, and proves that ESO has a robust system in place.

The VISTA SV projects — the Galactic and extragalactic mini-surveys

SV consists of the execution of two self-contained mini-surveys, one Galactic and one extragalactic, which were defined by teams of astronomers from ESO and the community. The execution of two mini-surveys in a single time allocation of two weeks allowed ESO to optimise the survey operations procedures, experience the full end-to-end process of survey data, and fulfill the goals of the science verification policy by providing the community with a complete and scientifically exciting set of new data.

The VISTA SV Galactic and extragalactic science cases are briefly described.

The Galactic survey project — Orion

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- QMUL/VISTA/CASU: Jim Emerson, Will Sutherland, Mike Irwin, Jim Lewis, Simon Hodgkin, Eduardo Gonzalez-Solares

The Orion star-forming region had been identified as an ideal VISTA SV target to study several aspects of star formation, early stellar evolution, and the interplay between OB stars and their immediate environment. In particular, an area of approximately 30 square degrees in the region of the Orion Belt, roughly centred at RA = 05h 32m, DEC = – 00° 18′, was chosen for a deep VISTA survey making use of all VISTA broadband filters (*Z, Y, J, H, Ks*). Orion is the closest giant molecular cloud at an average distance of ~ 400 pc, and has been actively forming stars within at least the last 10 Myr (e.g., Bally, 2008), which is about the timescale on which giant planets are thought to be formed. The VISTA–Orion survey area includes a number of stellar groups of different ages, among which are: very young (~ 1 Myr old) stellar clusters, sometimes still embedded in the molecular cloud material (NGC 2024, NGC 2023, NGC 2068 and NGC 2071, see Figure 1); the intermediate-age cluster σ Ori (age ~ 3 Myr); parts of the older stellar OB associations Ori OB1b (~ 5 Myr) and Ori OB1a (~ 10 Myr); as well as the recently identified stellar group of almost 200 pre-main sequence (PMS) stars around the B-star 25 Ori (~ 10 Myr).

One of the main goals of the Galactic VISTA SV project is to detect the young stellar and substellar populations present in the survey area, to a depth that goes significantly beyond current limits, and hence to investigate the substellar initial mass function (IMF) down to 10–20 M_{Jup}. This study will probe environmental effects and possible non-universality on the very low-mass end of the IMF. With targeted survey sensitivity limits of Z = 22.7 mag, Y = 21.0 mag, J = 20.2 mag, H = 19.2 mag and Ks = 18.4 mag, objects with masses as low as 12 M_{Jup} and as old as 10 Myr can be uncovered. At somewhat younger ages, e.g., 5 Myr, a 10 M_{Jup} object is expected to show a brightness of J = 19.4 mag and Ks = 18.0 mag at the distance of Orion (according to the DUSTY evolutionary models of Chabrier et al., 2000). The use of all VISTA *ZYJHKs* filters allows an optimal photometric selection of candidate pre-main sequence Orion members. Complementary data, for example from Spitzer and X-ray surveys, also provide helpful additional indications for the youth of individual candidate PMS objects. Since variability has been recognised to be another indicator of youth, a small subset of the survey has also been designed to study photometric variability on timescales of days in the field of the stellar aggregate around 25 Ori.

Additional goals of the survey include:
– A comprehensive spectral energy distribution analysis to search for optically thick discs and a further analysis of their evolution over a timescale of 1–10 Myr, the range of ages of the populations present in the VISTA–Orion survey. Understanding the evolution of accretion discs can provide strong constraints on theories of planet formation, and measuring the lowest mass at which young objects harbour circumstellar discs is crucial for determining whether planets can form around low-mass brown dwarfs.
– Detection of scattered light emission from the discs/envelopes of protostars detected by Spitzer observations in the Orion Cloud B. A wavelength coverage from the Z- to Ks-band of such structures is very useful for models of circumstellar envelopes, as they provide a direct estimate of the outflow cavity opening angles and orientations.
– Photometric variability of very low-mass stars and brown dwarfs.

Figure 1. This image shows a roughly 16 × 16 arcminute area of a VISTA tile taken on the Orion cloud B, observing the cluster NGC 2071. The centre of NGC 2071 shows up in scattered light (blue reflection nebulosity). Star formation activity is seen in the immediate surroundings of the cluster. The image is a colour-composite made from observations using the VISTA Z (blue), J (green), and Ks (red) filters. The image is tilted at position angle 15 degrees from north.

Observing strategy for the Orion survey

The survey consisted of observing 20 contiguous tiles covering a total area of ~ 30 square degrees, and with each tile being tilted by a position angle of 15 degrees. Each tile has a size of approximately 1 by 1.5 degrees and defines a fully covered area stacked from six VISTA pawprint positions. Furthermore, the tiles overlap by 60 arcseconds in the X-direction (i.e. along the shorter side of the tile) and by 100 arcseconds in the Y-direction. The creation of observation blocks for the survey area was facilitated by the mandatory use of SADT, which has been specifically developed for the preparation of extensive survey observations, and by using a newly designed P2PP.

In detail, the following strategy and respective OBs were adopted:

1) Deep imaging at *Z*, *Y*, *H*, *J*, *Ks* for each tile was accomplished by creating two OBs (per tile) that were concatenated, i.e. enforcing their execution in immediate consecutive order. The first OB defined *KsJZ* imaging with typical total exposure times per pixel in the stacked final tile of 96 s (*Ks*), 128 s (*J*), 900 s (*Z*) and two jitters per pawprint position, except for *Z*-band observations that use three jitters. The second OB defined *HYYZ* imaging with typical total exposure times per pixel of 96 s (*H*), 240 s (*Y*), 48 s (*Y*), 48 s (*Z*). Short exposures for *Y*- and *Z*-band with shorter DITs (Detector Integration Times) were performed in the second OB in order to have non-saturated images for the moderately bright objects. The OB execution in concatenation took approximately 2 hours and was motivated by the fact that young low-mass objects are known to be possibly variable on timescales of several hours to days. Hence, an almost simultaneous observation of a tile in all VISTA broadband filters can obtain the true shape of the spectral energy distribution of the sources. Since most regions in the Orion survey area do not show a strong nebulous background and little crowding, the sky was estimated from the science exposures of the tile itself. Tile 4, however, contains NGC 2024, which has extended nebulosity. Therefore, for this tile the sky subtraction strategy was to use the concatenated observations of Tile 4 with an offset sky field, east of NGC 2024, and with the Tile 8 observations to the north of Tile 4.
2) Shallower, repeated imaging of Tile 19, centred on the stellar group of 25 Ori were executed in order to search for variability of sources. An observation at *J*- and *H*-band (one short OB with alternating *H* and *J* observations with NDIT × DIT = 3 × 4 sec (*H*) and 2 × 8 sec (*J*) was executed at least once per night. But typically, two epochs per night were taken with a minimum separation of one hour in time between these two.
3) To improve the sensitivity for observations at *Z*- and *J*-band of Tile 16, which contains the well- studied cluster σ Ori, some additional OBs at *Z*- and *J*-band were prepared. These observations were used as fillers, i.e. were carried out only in case additional time was available, e.g., a few minutes (or tens of minutes) at the end of the observing night when it was not reasonable to start deep observations on a new tile. The settings used for these observations were NDIT × DIT = 3 × 30 sec (*Z*), 8 × 4 sec (*J*), with three jitters per pawprint position.

The extragalactic survey project – NGC 253

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- QMUL/VISTA/CASU: Jim Emerson, William Sutherland, Mike Irwin, Jim Lewis, Simon Hodgkin, Eduardo Gonzalez-Solares

The scientific project of the extragalactic mini-survey investigates the mass assembly history of a spiral galaxy in the context of the cold dark matter (CDM) structure formation scenario. This goal is achieved by using the abundance and properties of galaxy satellites, i.e. their mass function and metallicities, the detection of the brightest stars (supergiants, Asymptotic Giant Branch [AGB] and Red Giant Branch [RGB] stars) in the galaxy halo and in the stellar streams, and the detection of globular clusters and ultra-compact dwarfs in the galaxy outer halo. This information maps the galaxy assembly history, and the underlying galaxy mass distribution for a nearby edge-on spiral galaxy. Observationally, this project requires deep imaging in the *Z*- and *J*- broadbands, plus the NB118 narrowband. The deep narrowband imaging is required to map the opacity of the halo, as well as to probe the star formation rate at a redshift of 0.84 for Hα emitting galaxies.

The target of the extragalactic mini-survey is NGC 253, a barred Sc galaxy, seen nearly edge-on, in the Sculptor group at the distance of 3.94 Mpc (Karachentsev et al., 2003); see the VISTA image in Figure 2. It is one of the best nearby examples of a nuclear starburst galaxy. A wealth of data is available in the ESO archive: narrowband Hα, and (shallower) broadbands from the MPG/ESO 2.2-metre Wide Field Imager (WFI), and imaging and spectra of the nucleus obtained with SOFI and ISAAC. The deep image of Malin & Hadley (1997), reaching 28 mag arcsecond^{-2}, shows the presence of an extended asymmetrical stellar halo plus a southern spur. A very small portion of its stellar halo has been studied for distance determination, and the accurate distance (D = 3.94 Mpc) to the galaxy has been determined by resolving and detecting the RGB tip stars at I = 23.97 ± 0.19 in the outer disc observed with the WFPC2 camera on board the Hubble Space Telescope.

Complementary to the deep *J* and *Z* exposures, shallow *Y*, *J*, *H*, *Ks* images of NGC 253 are also required. The primary goal of a shallow survey is to model the disc and bulge components of NGC 253 and, together with the deep imaging data, to detect any signatures of an extended thick disc component. With the addition of optical data obtained from the WFI, along with a robust bulge plus disc decomposition, one can estimate the mass via luminosity and a colour-based mass-to-light ratio. Both the disc model and the large number of observed wavebands are also used to search for possible substructures in the disc and halo of NGC 253.

A summary of the scientific projects currently underway with the NGC 253 dataset is:
- Morphology of spiral arms and disc;
- Nuclear young massive star clusters and OB associations;
- Streams and satellite galaxy properties;
- Detections of globular clusters, ultra-

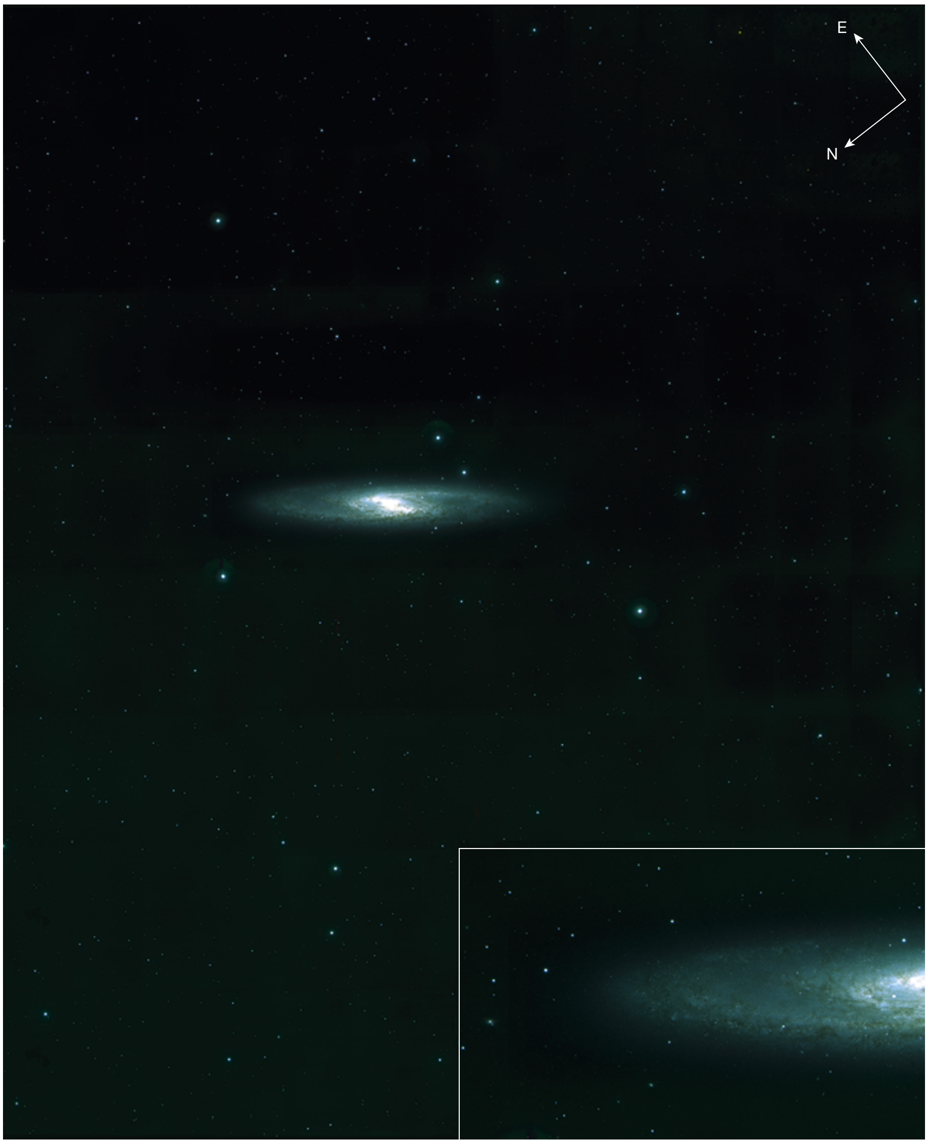

Figure 2. A VISTA image of the spiral galaxy NGC 253, located in the Sculptor Group, is shown. This true-colour image consists of co-added VIRCAM tiles in the *J*-band (red), narrowband 1.18 microns (green), and *Z*-band (blue). This 200-Megapixel image tile has a physical dimension of 1.21 × 1.49 degrees, and impressively demonstrates VISTA's field of view (with the detector gaps filled in the tile). The long axis of the camera is aligned at position angle 52 degrees, and north is to the left and east is up. The inset shows a zoom of the north-eastern spiral arm of NGC 253. Complementary to the extremely large field of view attainable with VISTA, this image shows the good image quality achieved during the VISTA SV. Data processing and tile creation courtesy of CASU.

compact dwarfs, dwarfs in the galaxy halo and their physical properties;
– Detection of RGB stars in the NGC 253 halo, their magnitudes, metallicities and spatial distribution;
– High-*z* galaxies and the extinction in NGC 253 halo by counting background galaxies.

Observing strategy

The geometry for the survey consisted of a single tile rotated at position angle 52 degrees so that the major axis of the galaxy was parallel to the shorter side of the tile: the wide VISTA field-of-view and the adopted orientation of the camera allows the survey of about 50 kpc above and below the galaxy disc. With this camera orientation, the disc of NGC 253 is centred on detectors 10 and 11 for pawprints 2, 4 and 6, so that the other three pawprints (1, 3 and 5), and their jittered exposures can be used to create an offset sky image for data processing.

The following observing strategies were adopted: 5.8 hrs in NB118 (NDIT × DIT = 1 × 300 sec), 9.6 hrs in *Z* (NDIT × DIT = 3 × 60 sec) and 24 hrs in *J*-band (NDIT × DIT = 5 × 45 sec) to detect the tip of the RGB stars. We used a sequence of six pawprint exposures nested within a sequence of five jitter offsets. Such a strategy was adopted to ensure the best sky subtraction: the presence of an extended disc covering several detectors would prevent simple sky subtraction using images from different jitter exposures, because the disc is both bright and extended. Having adjacent pawprints made it possible to subtract the sky. This approach had an impact on the data reduction and identified the need for the definition of a sky template.

The shallow observing strategy included short observations in *Y*, *J*, *H* and *Ks* to study the morphology of the disc, the bar and the nuclear regions, and the mapping of the thick disc. Here the implemented strategy tested a possible sky-offset sequence. A concatenation was made with three OBs, the first and the third were centred on the galaxy with the assumption that they would cover two parallel stripes. The second OB was a single pawprint observation of an offset sky. This approach failed because of a mistake in implementation of the SADT definition of some tiles, which was then solved in the official SADT release for the Phase 2 call. The observing strategy was changed on-the-fly and shallow observations with the correct coverage were obtained using the same observing strategy that had proved to work for the deep survey.

The definition of the geometry of the mini-surveys via SADT, and the Phase 2 OBs are available on the VISTA SV web page[1].

VISTA SV — input requests from the PIs

On the basis of the Public Survey Panel's recommendation, the Principal nvestigators (PIs) of the public surveys were invited by the ESO Director General during the Phase 2 workshop to submit their OBs for targeted observations (up to two hours duration) with observing modes that were not covered by the VISTA SV observing strategies. Details of the VISTA public surveys can be found in Arnaboldi et al. (2007). Public survey PIs Minniti (VVV), Cioni (VMC), Jarvis and Dunlop (VIDEO and UltraVISTA) requested short observations during the VISTA SV for their dedicated tests. More information on the observing strategies and the associated data products are also available on the VISTA SV web pages[1].

VISTA SV — visitor mode observations

Observations were carried out in visitor mode and the observers were Arnaboldi, Hilker, Petr-Gotzens and Rejkuba from 15 October to 3 November 2009. Support astronomers were Szeifert and Ivanov. A complete observing log is available from the VISTA SV web pages[1]. The weather conditions were good for most of the nights with typically clear or photometric atmospheric conditions and seeing ≤ 1.2 arcseconds. Four nights were lost due to weather and technical problems. The galaxy NGC 253 was observed during the first half of the nights at airmasses less than 1.5. Orion was then observable during the second half of the nights, after it had risen above airmass 2.0.

Pawprint-level data products for about 60 % of the observations of the extragalactic mini-survey, and 10 % of the Galactic mini-survey were produced at the Paranal Observatory, in parallel with the observations. The reductions were run on the offline machine with the VIRCAM pipeline version 0.9.6. The reduction blocks were manually adjusted in order to use the latest calibrations available, and include the offset frames for sky subtraction. The OB-level data products consist of stacked jittered images for each pawprint, associated photometric catalogues, confidence maps, as well as offset sky images. These reductions enabled the ESO astronomers involved in the user support and science operations to gain experience with the VIRCAM pipeline and data processing, and to investigate some validity ranges of the different parameters, i.e. de-striping, and the best observational strategy for offset sky observations. At the same time important VIRCAM template parameters and instrument characteristics were measured as described below.

Reductions of SV data beyond the pawprint level — production of tiles, mosaics and band merging of the catalogues — are on-going activities coordinated in ESO Garching by the SV team PIs, Arnaboldi and Petr-Gotzens, and in CASU by Irwin.

VISTA SV — feedback to science operations and user support

The observations carried out during the VISTA SV provided very useful tests on the Phase 2 tools and the science operation in service mode. The results of these tests and the actions taken are briefly described.

The ESO astronomers verified the consistency between the definition of the survey geometry of executed OBs and the acquired frames via the astrometry calibration applied by the VIRCAM pipeline to the OB data products. Important SADT input parameters, e.g., the tile overlaps, tile orientation on the sky and the combination of six pawprints into a tile, were verified with the corresponding data products. The new concepts of the scheduling containers implemented for the first time in the P2PP version for surveys were tested and executed during the VISTA SV. OBs were defined using Time Link, Concatenation, and Group scheduling containers. The implementation at the P2PP level is working well.

The VIRCAM templates allow the use of multiple filters in a single OB. The nesting of different filters, different pawprint sequences and jittering offsets needed to be verified during SV. All available configurations were used and most of them successfully executed. In the case of problems, they were either documented or actions taken to solve them before the Phase 2 call. The overheads for OB execution were measured during the ESO commissioning run in July 2009 and implemented as part of P2PP for the verification of the OBs carried out by the user support astronomers. The overheads were tested during the execution of the SV OBs and further verification is expected during the regular service mode operations, with more robust statistics on a larger number of OBs.

The VIRCAM detectors were tested for persistence, linearity and saturation level. Results based on the observations of bright stars in the Orion survey indicate that only a very low level of persistence is measured. For a star with $K = 2.2$ mag (HD 36558) a persistence signal of 1.5 σ above the background was detected 1 minute after the saturation occurred. No persistence at all is measurable after 2 minutes. Filters were checked for fringing and none was detected. Linearity and saturation tests were carried out during the VISTA commissioning, and the related information is available from the CASU web page[2].

The intensity of the sky background was monitored during the evening twilight. A long sequence of observations was acquired in *J*- and *Z*-band for the NGC 253 mini-survey, and the frame sequence shows a strongly decreasing background as a function of time from the evening twilight for the *J*-band, and a shallower decrease in the *Z*-band, see Figure 3.

Feedback to the VISTA Data Flow System

To ensure an early feedback of the VISTA SV results into the Vista Data Flow System (VDFS) , a two-day meeting of the ESO SV team and CASU representatives was organised at ESO on 25–26 November 2009. In the current setup, the VISTA raw data reach CASU one week after they are ingested into the ESO archive; all the data taken with VISTA are processed by CASU, and then transferred to the other VDFS component, the VISTA Science Archive (VSA) at the Wide Field Astronomy Unit (WFAU) in Edinburgh. An important aspect of the operations is that the night logs are very important for the processing of scientific data. Therefore channels for the information to flow both from ESO to VDFS components in the UK and vice versa need to be specifically established, and some areas for improvement were identified.

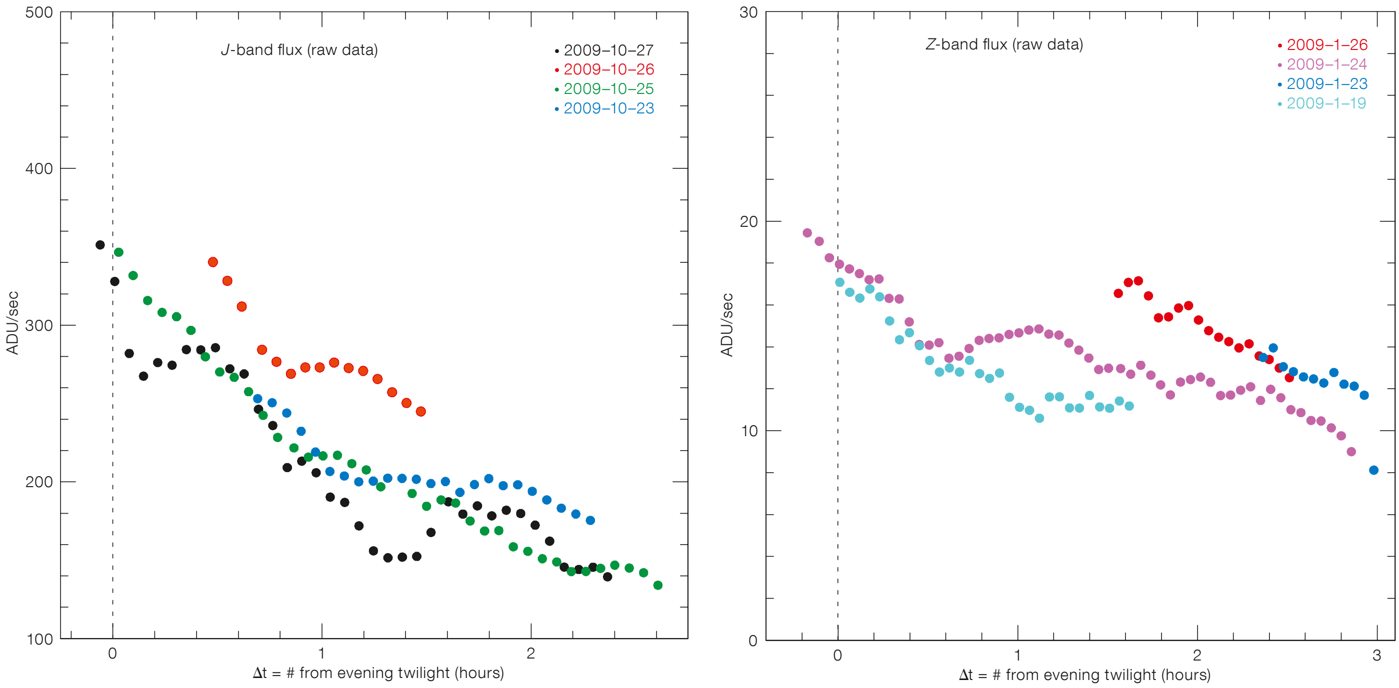

Figure 3. Background flux *vs.* twilight time distance: *J*-band (left panel) shows a rapid decrease in background flux within the first hour from the evening twilight, while the effect is smaller for *Z*-band (right panel). These measurements were made on raw images, but in all cases DIT and NDIT values were the same.

VIRCAM detectors have about 1–10 % deviation from linearity and saturate at about 24 000–37 000 ADU. To ensure the use of VIRCAM detectors in the linearity regime, VISTA users are advised to adopt short integration times, e.g., DIT < 10 s for *H*- and *Ks*-bands. Science operations in Paranal have implemented a careful monitoring of flats in the different bands taken at sunsets, as they can easily be outside the linearity regime.

Both the astrometric and photometric calibration were discussed at length by the ESO and CASU astronomers. The astrometric calibration implemented by the VISTA pipeline seems to work well in the Orion fields, but had some problems in the case of the NGC 253 bright disc. Since it depends on the 2MASS catalogue, when the reference stars are affected by spurious detections because of crowding of bright extended objects in the field, the astrometric calibration computed by the pipeline is not correct. SV data uncovered this problem and allowed more robust quality checks on the 2MASS star catalogue to be established. An updated version of the VISTA pipeline now handles the astrometry correctly. *JHKs* photometry and zero points are computed for each detector by comparison with 2MASS photometry for the same stars. The *Z*- and *J*-bands can be calibrated from the linear relation with 2MASS *J–H* colour, and the independent zero point calibration via standard fields taken during the night.

Publications of VISTA SV data and next steps

The raw data and master calibrations of the two mini-surveys executed during the VISTA SV were published on the dedicated VISTA SV pages[1] and became available worldwide on 21 December 2009. They can be downloaded via the ESO archive web pages; users should be reminded of the large size of these images!

The VISTA SV team is also planning to publish the data products produced by the VDFS pipeline and the advanced data products, e.g., complete mosaicked pawprints into tiles and band-merged catalogues, as soon as these are scientifically validated. Access to these data products via the ESO archive will provide the astronomical community at large with a set of VISTA data ready for scientific exploitation.

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Links

[1] VISTA SV webpage: http://www.eso.org/sci/observing/policies/PublicSurveys/VISTA_SV.html
[2] CASU webpage: http://casu.ast.cam.ac.uk/surveys-projects/vista/technical/linearity-sequences