# The VLT Survey Telescope Opens to the Sky: History of a Commissioning

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**The VLT Survey Telescope (VST) is now ready to undertake its mission. After a long gestation, the telescope has revealed its power, providing image quality and resolution beyond expectation. This achievement has been made possible by a motivated team of scientists and engineers who have brought the VST to its current state of readiness for survey science. This paper briefly reviews the latest stages of the project and the characteristics of the VST, and lists the scientific programmes for the observing time guaranteed by ESO to the Italian community in return for the procurement of the telescope.**

## Introduction

The VLT Survey Telescope (VST) is a wide-field optical imaging telescope with a 2.61-metre aperture, operating from the ultraviolet to the near-infrared ($z'$-band) with a corrected field of view of 1 degree by 1 degree. Views of the VST in its dome are shown in Figures 1, 2 and 3. Conceived for the superb environment of the Paranal Observatory (Figure 4), it features an f/5.5 modified Ritchey–Chretien optical layout, a two-lens wide-field corrector with the dewar window acting as a third lens or, alternatively, an atmospheric dispersion compensator coupled with a single-lens wide-field corrector plus the dewar window, an active primary mirror (Figure 5), a hexapod-driven secondary mirror, and an alt-azimuthal mounting. Its single focal plane instrument, OmegaCAM, is a large format (16k × 16k pixels) CCD camera contributed by the OmegaCAM consortium (see Kuijken, p. 8).

The VST is the result of a joint venture between ESO and the Capodimonte Astronomical Observatory (OAC) in Naples, formerly an independent institution, and, since 2002, part of the Italian National Institute for Astrophysics (INAF). It is the largest instrumental project carried out by Italian astronomy for ESO and the first active optics telescope completely designed in Italy, from scratch, and by a fistful of engineers.

Here we briefly describe the final stages of the project before its completion and report on the scientific programmes devised by the INAF community for the guaranteed time observing (GTO). For the earlier history see Capaccioli et al. (2003, 2005).

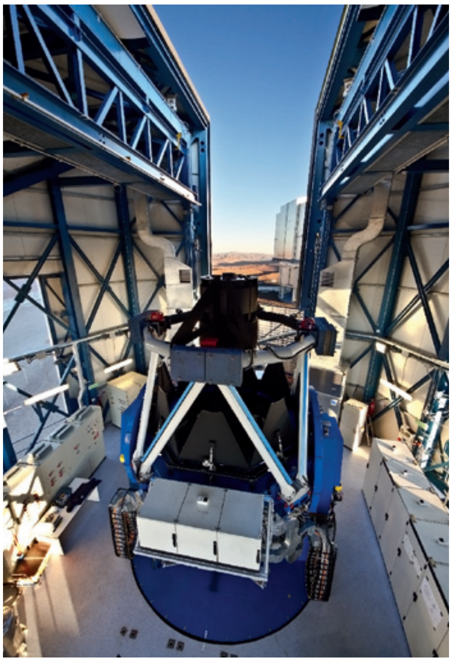


Figure 1. A view of the VST inside its enclosure, surrounded by the electrical control cabinets. UT4 and the Atacama desert are visible in the background.

## Early development

The VST project was proposed by OAC to ESO in 1997 and began in 1998 with the signature of a Memorandum of Understanding (MoU) establishing the dues and rights of the partners. OAC committed to procuring the telescope and providing up to two of its personnel to support the operation of the facility. In return, OAC (now part of INAF) was entitled to receive a proportional share of the total VST observing time plus a number of nights at one VLT Unit Telescope (UT). ESO committed itself to provide the facilities needed to house and run the telescope at Paranal, to cooperate with OAC in setting the specifications and interfaces of the telescope, to procure the transport of the instrument from Italy to Chile, to secure the proper CCD camera, and to commission the complete VST system. Moreover ESO took responsibility for the operation and maintenance of the VST for a period of ten years.

In the summer of 2011 ESO and INAF amended the MoU and agreed on the following share for the INAF–GTO: 10% for the first four years of the telescope's life, 15% for following two years, and 20% for the remaining four years (percentages to be calculated at the net of the Chilean time). These numbers reflect the effort made by INAF to boost the ESO Public Surveys, and take into account the delays in the project. INAF was also granted a number of hours, equivalent to 28 nights at one VLT UT, to be evenly distributed over an interval of ten years and to be used exclusively for follow-up programmes for INAF–VST surveys.

The development of the project was marked by two major accidents which have extended the schedule significantly: the first back in 2002, when the primary mirror (M1) was literally shattered during its transfer by ship to Chile. Recovery from this took almost four years, while the Russian firm LZOS, which had very successfully manufactured the first mirror, completed an exact replica. In addition to the time delay, it had grave collateral effects on the motivation of the VST technology team at OAC and on the budget (see Capaccioli et al., [2005], for more details).

In 2002 the Italian observatories were merged into the National Institute for Astrophysics, which had the critical mass to sustain OAC in this dramatic phase of

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Figure 2. The VST from above. The M1 cover is open and the primary mirror is visible with its baffle. On top, the back side of the hexapod driving M2 is visible. The observation doors with the wind screen are seen on the right side of the picture.

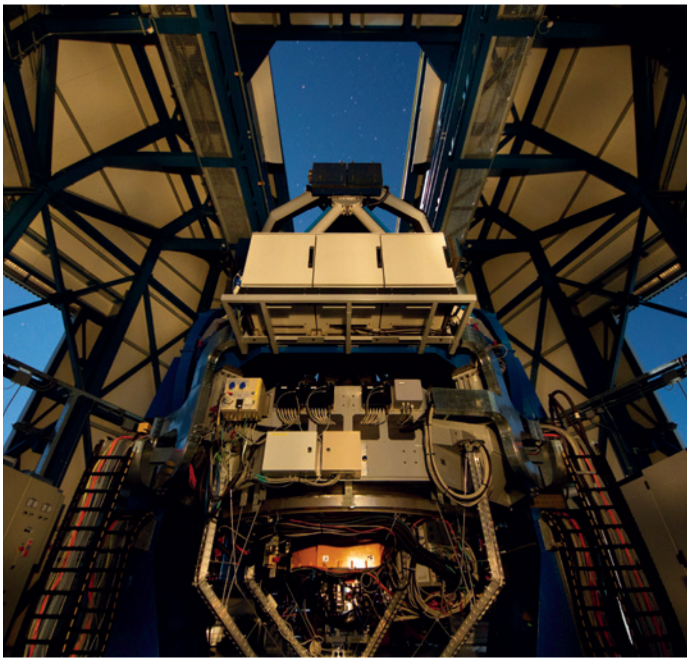

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Figure 3. The VST as seen from the observing floor. The OmegaCAM instrument and its control cabinets are in the lower section, interfaced to the telescope at the Cassegrain focus.

the project. In addition to money, INAF provided managerial and technological support using the knowhow available in its other structures, increasing the staff complement by bringing in people, mainly from the Padua Observatory. In late 2005 INAF also created an *ad hoc* institute, based at Capodimonte and named VSTceN, to coordinate the project, which was placed under the direction of Massimo Capaccioli, former OAC director and the principal investigator of the VST.

By March 2006 the new primary mirror, with which the active optics sub units had to be carefully matched, had safely reached the Paranal Observatory, and by the end of the year an ESO audit team spent about one month with the OAC team in Naples and concluded that the telescope mount and the tracking system, pre-assembled at the MecSud firm in Scafati, were ready for shipping to Chile, which was done during 2007. The telescope was then re-integrated and tested at Paranal. In the same year, the Critical Design Review (CDR) of the primary and secondary mirror systems, which should have given the green light to these crucial units, was globally unsuccessful. Of course, the immediate feeling at OAC was of considerable disappointment! But looking back, this failure marked the turning point for the later success. The key problem identified by the ESO reviewers was a lack of proper systems engineering in the project, which had been diluted by the considerable efforts made on the single subsystems.

## Recent progress

Starting from mid-2007, the primary and secondary mirror support systems were extensively reconsidered by INAF–OAC at the systems engineering level, transferring the technical leadership to P. Schipani and establishing a new team with some of the engineers who had already been working on the project. The re-design of the active optics system was further complicated by two stringent conditions: to minimise the changes and the expenditures and to close out the activities as soon as possible.

This strategy led to success: in a little less than two years, including manufacturing and tests, all the parts of the telescope still in Italy received the green light to be shipped to Chile. The telescope error budget was revisited and the concept of the primary mirror support and safety system redesigned, with regard to performance, reliability, and maintenance operations. The error budget was modified, adopting ambitious, but realistic, capabilities for the telescope subsystems. Two major simplifications were introduced into the active optics subsystems. The 24 lateral active supports in the M1 cell were replaced by passive astatic levers, and three lateral fixed points were introduced. In addition, the piezoelectric plate, with five degrees of freedom, coupled to the hexapod for the accurate positioning of the secondary mirror (M2) was eliminated, with no real loss of accuracy and a major gain in reliability and operability.

The primary mirror support system design, the control software and the electronics were updated by INAF–OAC, and the new mechanical parts were designed by Tomelleri srl, the firm which also re-cabled the cell, under VSTceN requirements and supervision. The earthquake safety system, previously overlooked, was designed in a joint effort led by INAF–OAC, which made the analysis jointly with BCV srl, and with full support from ESO's Technology Division, while the mechanical design was committed to Tomelleri srl.

The concept of the secondary mirror support system was also significantly updated by INAF–OAC in order to improve reliability and performance. The mechanics of the hexapod were slightly improved by ADS International srl, while the modification of the control electronics was shared between ADS for the leg electronics and VSTceN for the Local Control Unit. New control software was written at INAF–OAC, replacing the old version made obsolete by the new hardware. At the end of 2008 the secondary mirror support system was effectively tested at system level and shipped to Chile, where in early 2009 it was installed at the telescope and verified on site. The secondary mirror could now perform relative displacements along the optical axis with a precision of about 0.1 μm (budget: 0.5 μm), and in the *XY*-plane with precision of 1–2 μm (budget: 5 μm) at any altitude angle.

Both the primary and the secondary mirror support systems were extensively tested in Italy in all gravity conditions using tilting test devices, undergoing severe qualification of both performance and reliability. A good MTBF (mean time between failures) was assessed by intensive tests on a subset of ten M1 actuators, simulating years of work of the support systems with uninterrupted 24-hour testing performed for several weeks at an accelerated rate.

## New accident, new recovery

In early 2009 the support system was ready to be shipped. Unfortunately, another major transport accident occurred. The vessel carrying the mirror cell, which had left Livorno at Easter, was delayed around Toulon by a general average. Two months passed before the ship set out again for Chile, but once the load reached Paranal it became apparent that a fair amount of water had penetrated the moisture barrier bag protecting the M1 cell and had caused severe damage.

The cell had to be re-imported back to Italy for re-manufacturing and qualification of the whole system, and, in particular, of the most critical component of the whole telescope, the primary mirror supports. This phase ended with successful system tests in April 2010. The accident had further shifted the schedule of the project back by one year. The recovery activity was supposed to be a "mere" repetition of the work already done but, surprisingly, the replacement of some obsolescent commercial components by nominally identical parts caused unexpected problems which were solved by changes in the control system. In the end the primary mirror supports turned out to have very good differential force setting capability; they perform small differential force adjustments generally with an error of just ±0.2 N, better than expected (budget: ±0.5 N).

With a few months of hard work, in early 2009 a team composed of people from Padua (Observatory and University), Capodimonte and INAF Headquarters, together with the industrial support of Tomelleri srl, completed the work on the remaining subsystems: adapter/rotator, probe optics, Shack–Hartmann wavefront sensor, atmospheric dispersion corrector (ADC), were all tested and debugged for the electromechanical part. The technical CCD systems were also put into operation. These units were shipped to Chile in mid-2009 and reassembled on site.

Meanwhile, other activities continued. The telescope control software was improved and tested, using the VLT control model facility at ESO Headquarters; a cabling plan was prepared and then followed during the integration; some parts of the cooling system were revisited because the old design did not fulfill all the real needs; the active optics operating model was studied in detail; the wavefront sensing was simulated; much optomechanical integrated analysis was carried out; the software interface with OmegaCAM was tested; the transfer function of the axes was measured both in Naples and again in Paranal, giving an altitude-locked rotor eigenfrequency of 9 Hz, in reasonable agreement with the control simulations; and many much less significant activities were also performed.

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Figure 4. The total complement of telescopes on the Paranal platform: the UTs and the auxiliary telescopes are joined by the latest addition of VST on the right side (north-east).

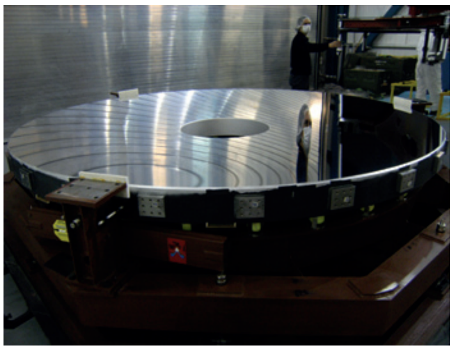

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Figure 5. The 2.6-metre VST primary mirror in the coating plant.

## Recent years in Chile

The reintegration in Paranal was performed in three different steps, always in strict collaboration with ESO. The first was the installation of the hydrostatic bearing system for the azimuth rotation and of the telescope mount, which ended in 2008. In 2009 the remaining parts of the telescope were shipped, but only the secondary mirror support system was put in place, due to the damage to the primary mirror cell. The missing work was completed in 2010 when the mirror cell returned to Paranal (never had a mirror cell travelled so much!), allowing the installation of the mirrors, adapter/rotator and ADC. The mirrors were coated and installed in the telescope with the close collaboration of ESO, Tomelleri srl and ADS International srl. The missing parts of the cooling system were also installed by EIE srl.

By the end of 2010 the telescope was integrated and pre-aligned. There were some missing details, but also great urgency: the commissioning team therefore accepted that the missing aspects would be taken care of in parallel with the night work, starting in January 2011. Then a fourth large integration step was taken: the installation of the camera in March 2011 by the OmegaCAM consortium, with some involvement of the VST commissioning team for the electromechanical interfaces and the final balancing of the telescope. The latter is now balanced with a remarkable 3.6-tonne counterweight on the top ring, which fortunately did not detract from the good tracking performance.

## Commissioning

Commissioning is the last fundamental step, i.e. the transformation of a big piece of iron and glass into a telescope. At the time of writing, this stage has just been successfully completed.

The commissioning of the telescope and of its camera should take place together, because OmegaCAM needs a working VST to be tuned and vice versa. The management of this interaction between the teams of OmegaCAM, ESO and VST could have become critical. But the good relationships established with the other teams nullified this risk: a human addition to a technical success in this case. The INAF team, composed of about ten people from Capodimonte, Padua and Arcetri, enjoyed the collaboration with OmegaCAM and ESO, as well as with the Dalkia engineering people hired in Paranal (the first light photo is shown as Figure 1 in Kuijken p. 8).

It must be added that the relatively small mirror diameter does not simplify things much with respect to a 8–10-metre telescope; in fact, it can make life even harder due to lack of space and reduced accessibility. Nevertheless, the commissioning of the VST was planned to take only a few months, including the camera commissioning. Everybody knew that this was an ambitious goal, but not unrealistic, for two reasons. First, the massive amount of preparatory work: there was little to invent from scratch on the mountain. Second, ESO support: the INAF team could always count on the Paranal people. In addition, one of the best ESO telescope control experts and the Garching guru of active optics joined the team. The commissioning plan was strictly followed and completed on time. Nevertheless, at the end of the scheduled activities, we realised that the image quality of the telescope on the whole field of view could be improved by additional shimming, discussed below, which was done in July 2011.

## Pointing and tracking

Work on the axis control loops was expected to proceed smoothly, because the loops had already been successfully tuned in Italy in 2006 and we were confident we could do it again. This was the case: no real show-stoppers were encountered; also for the pointing model and autoguiding, which of course had never been tested before. The pointing accuracy is at the level of 1 arcsecond root mean square (rms), with a best score of 0.8 arcseconds so far. The tracking axes have a blind tracking error against their own encoders of the order of a few $10^{-2}$ arcseconds rms, lower than specification. The VST guiding system with its guide probe is fully operational and enables an image centroid error on the guide probe smaller than 0.1 arcseconds. Good performance was also maintained during windy nights, with wind speeds up to 18 m/s, by closing the ventilation doors and using the wind screen.

## Active optics

The active optics was indeed an exciting part of the job. That system had been the major recent concern; we had to prove the effectiveness of the new concepts that we had implemented for the primary and secondary mirror support systems. This was relatively straightforward. After two nights of work we had successfully converted the Shack–Hartmann aberration angles into M1 and M2 coordinates and the active optics loop had been closed: we could already reduce the amount of aberration we saw on the workstation panels. But still there was a hidden problem, which we only discovered some weeks later: the Shack–Hartmann sensor suffered from static aberrations in the non-common path, which was dominant for some modes with respect to the real aberrations of the telescope. In other words the measurement was corrupted, but we were able to make a software fix.

Another major improvement was also necessary: by design the primary mirror support has no passive system that automatically compensates for the change of axial weight. This caused, as expected, incorrect forces on the three axial fixed points if no action was taken, especially at large zenith angles, generating trefoil aberration. The other M1 aberration modes proved to be much more stable. In order to be compliant with any operational scheme, we removed the root cause of the trefoil with a background software task that makes the system astatic. The active optics system is now fully operational: the aberration coefficients measured by the Shack–Hartmann sensor can usually be reduced to an acceptable level in two iterations.

## Alignment

The alignment was one the hardest parts of commissioning, because the wide

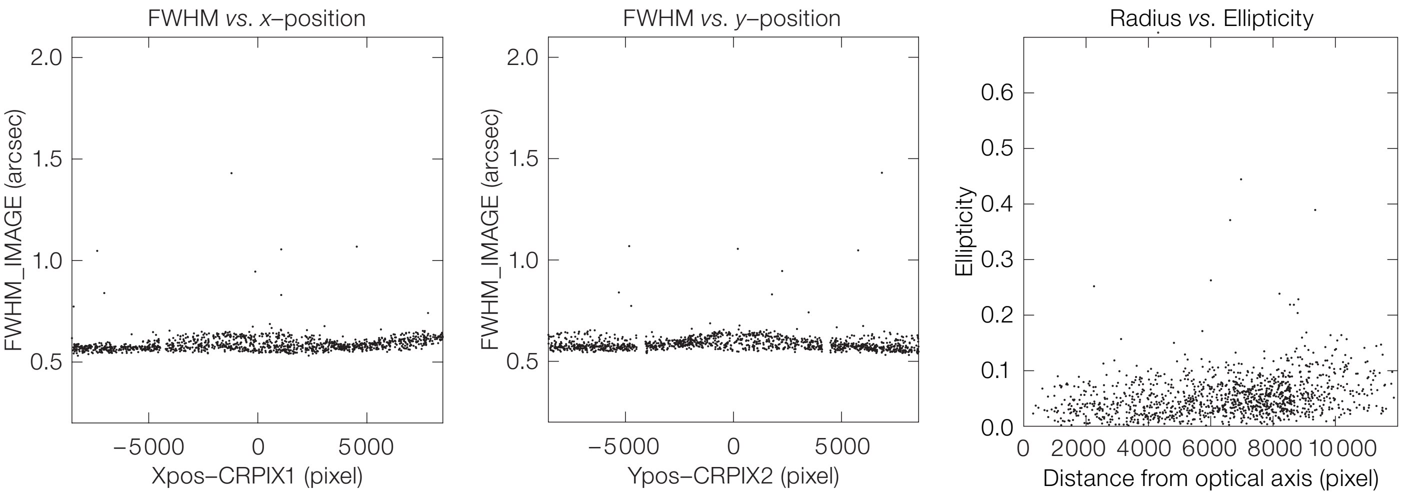


Figure 6. Image full width at half maximum *vs. X* offset (left) and *Y* offset (centre) are shown to be homogeneous after the alignment of rotator and optical axes. The image ellipticities, shown at right as a function of radial offset, are mostly within 10%.

field imposes much tighter requirements than for a normal telescope. We could remove a large amount of off-axis astigmatism by aligning M2 with M1: once we knew the correct measure, the correction was easily implemented using the hexapod. But the telescope still suffered from a focus gradient. Indeed, after the installation of the camera, a misalignment between the rotator and the optical axis was clearly detected. This had negligible effects on about 70% of the image, but caused a degradation on one side of the mosaic, which was out of focus. This problem could only be solved by shimming the rotator flange, with a lot of mechanical work and some suspense over the angle of the shims, which was fortunately correct! Now the image quality is homogeneous over the whole mosaic as expected by design (see Figure 6).

## Prospects

During commissioning the telescope has reached a good level of performance, as discussed above. Last but not least, the system has regularly worked for the whole duration of these activities with a technical downtime less than we could optimistically have expected for such a phase. The VST commissioning process has finally concluded with the Preliminary Acceptance Chile (PAC) being granted by ESO.

As a consequence of all this testing and the concomitant reliability, the telescope is already delivering seeing-limited images, with seeing measured by the Astronomical Site Monitor down to 0.4 arcseconds. Thus, it is now ready to survey the sky, and we are ready to work on the images using both AstroWise, the software package developed by the OmegaCAM consortium, and VST-Tube, another package designed at OAC to process VST images specifically. This latter package is an automated pipeline going from the raw exposures to fully calibrated co-added images, and extraction of catalogues with aperture and point spread function photometry. A set of tools allows us to administrate the data and check the quality of the intermediate and final products. VST-Tube comes with a Graphical User Interface to facilitate the interaction between data and user. The capabilities of this software have been recently proven as it was applied to produce the monochromatic images combined by ESO for the picture of the globular cluster Omega Centaurus (front cover image). In passing we note that a preliminary reduction of these images leads to limiting stellar magnitudes that are perfectly consistent with the expectations.


## Acknowledgements

The proposal, study, design, and realisation of the VST telescope was the result of the joint effort of a number of people who are acknowledged here as a whole. The following list is just for the last few years. Even so, it is quite long and we run the risk of forgetting someone (for which we apologise in advance).

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# Appendix: Overview of INAF–GTO Surveys

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The VST/OmegaCAM facility provides multiband images of unprecedented quality, suitable for the investigation of a range of cutting-edge issues, such as the constituents of the Milky Way and its companion galaxies, the structure of nearby galaxies, galaxy formation processes in different environments from the field through clusters to superclusters, the search of intermediate redshift supernovae, the search/study of Active Galactic Nuclei (AGNs) and quasars, and finally the study of dark matter distribution in the Universe by weak lensing. Of course, based on previous experience with survey telescopes, a major outcome can also be expected from serendipitous discoveries.

The science division of VSTceN (for several years led by Juan Alcalà Estrada) has cooperated with the PIs of the INAF–GTO survey programmes with the aim of monitoring their degree of competitiveness. Following revision in 2008 some of the surveys were dropped. In 2009, just before the accident to the VST cell, INAF and VSTceN organised a workshop in Naples to discuss the current programmes and gather new ideas for VST–GTO exploitation. This led to a call for letters of intent. A comprehensive summary of the projects was presented at the ESO VST Public Surveys and GTO Programmes Review meeting in 2010 resulting in a synthesis which took into account the synergies among GTO projects and ESO Public Surveys. Brief summaries of the INAF–GTO programmes follow.

SUDARE: Supernova diversity and rate evolution
PI: Enrico Cappellaro (INAF–Padua Observatory)
The aim of the survey is to measure the rate of the different types of supernovae (SNe) at redshift $z \sim 0.3$–$0.6$ and, by comparison with local rates, probe the evolution of SN diversity with cosmic time. Statistics of SNe in different environments and as a function of redshift are a key test of the coherence of stellar evolution theory, SN explosion mechanisms and the relation between nucleosynthesis and galaxy evolutionary scenarios, through some of their basic ingredients, namely star formation history, chemical enrichment, and feedback effects. The project is also intended to build up experience and test tools that will be needed for future all-sky synoptic surveys.

STEP: The SMC in Time: Evolution of a Prototype interacting late-type dwarf galaxy
PI: Vincenzo Ripepi (INAF–Capodimonte Observatory)
The intent is to derive the color–magnitude diagrams of the oldest population of the Small Magellanic Cloud (SMC) down to 1–2 magnitudes below the main sequence turn-off. This will help to break the age–metallicity degeneracy and recover the star formation history of the galaxy and of the Magellanic Bridge. Classical variable stars (RR Lyrae, Cepheids, anomalous Cepheids, δ-Scuti stars, etc.) will be used as population tracers, especially in the unexplored region of the Bridge. The survey, which is synergic with the VISTA Public Survey VMC, will also shed light on the first stages of star formation by securing a complete mapping of pre-main-sequence objects.

STREGA@VST: Structure and evolution of the galaxy
PI: Marcella Marconi (INAF–Capodimonte Observatory)
This survey addresses the issues of the formation mechanisms in the Galactic halo by: i) tracing tidal tails and haloes around stellar clusters and galaxies; ii) mapping extended regions of the southern portion of the orbit of the Fornax dwarf galaxy; iii) possibly identifying new very faint stellar systems using recent techniques developed by the Sloan Digital Sky Survey (SDSS). Stellar tools will be used to achieve the science objectives: variable stars (RR Lyrae and long-period variables), turn-off and main sequence stars.

Extension in the *u′*-band of the WINGS Survey (Wide field Imaging of Nearby Galaxy clusters Survey)
PI: Mauro D’Onofrio (University of Padua)
The survey aims at obtaining deep *u′*-band images for ~ 50 galaxy clusters in the redshift range $0.04 < z < 0.07$, which already have complete *B, V, J, K* and spectroscopic information from the WINGS survey. The *u′*-band imaging of the WINGS clusters gives a first chance to study in detail the star formation activity in a statistically significant sample of cluster galaxies and to establish the correlations between such activity and the galaxy morphology (from *V*-band imaging) and masses (from *K*-band data), and the link with the environment.

VST-ACCESS (A Complete CEnsus of Star formation and nuclear activity in the Shapley supercluster)
PI: Paola Merluzzi (INAF–Capodimonte Observatory)
This is a multiband (*u′, g′, r′, i′, z′*) survey project aimed at determining the importance of cluster assembly processes in driving the evolution of galaxies (down to $M^* = +6$) as a function of their mass and environment, by covering a field of 23 square degrees centred on the core of the Shapley supercluster ($z = 0.048$). It will be possible to track the evolution of galaxies from field to filaments and groups up to the cluster cores and to investigate what is the primary location for galaxies to be transformed. The survey will extend the multi-wavelength (far-ultraviolet to far-infrared) ACCESS survey ongoing in the supercluster core.

VOICE: VST optical imaging of the CDFS and ES1 areas
PI: Giovanni Covone & Mattia Vaccari (Universities of Naples & Padua)
VOICE is a multiband (*u′, g′, r′, i′* to *AB* ~ 26) optical survey of the central regions of the Chandra Deep Field-South (CDFS) and ES1 fields (8 square degrees in total). These areas are of paramount interest for the community as they have been, and will be, targeted by deep ultraviolet (GALEX–DIS), near-infrared (VISTA–VIDEO), mid-infrared (Spitzer–SERVS and Spitzer–SWIRE), far-infrared (Herschel–HerMES), and radio (ATCA–ATLAS) surveys. The uniform and deep optical coverage still missing on these fields will be suitable for galaxy formation studies out to $z \sim 1$ and for gravitational lensing.

VEGAS: VST survey of Elliptical Galaxies in the South hemisphere
PI: Massimo Capaccioli (University of Naples Federico II)
This deep multiband VST survey of nearby elliptical galaxies in the southern hemisphere is expected to reach 27.5, 27.0, 26.2 mag arcsecond$^{-2}$ in *g′, r′, i′*, respectively. The aim is to: i) trace the light distribution out to ten effective radii ($R_e$); ii) derive colour gradients and measure the surface brightness fluctuation gradients out to a few $R_e$, for stellar population characterisation; and iii) obtain a full census of the satellite systems (globular clusters and dwarf galaxies) out to 20% of the galaxy virial radii.

A VST-OmegaCAM survey of Local Group dwarf galaxies
PI: Enrico Held (INAF–Padua Observatory)
The survey aims at carrying out a multiband (*B, V, i′, u′*) wide-field survey of southern Local Group dwarfs, extending well beyond the current nominal tidal radii. The survey will represent the most complete mapping of dwarf galaxies and provide useful targets for follow-up spectroscopy as well as an insight into the variations of the stellar populations. The proposal is based on both OmegaCAM and INAF–GTO.