Science Verification of the VLT Unit Telescope 1

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Introduction

The VLT first Unit Telescope (UT1) is now being commissioned, and ESO is committed to deliver to its community a fully tested and understood telescope by April 1, 1999. To this end, brief periods of Science Verification (SV) are now planned for the telescope and each of its instruments. SV data will become immediately public within the ESO community, and will offer the earliest opportunity of scientific return from the VLT and its newly installed instruments. Feedback from early users is expected to be an integral part of SV, with the understanding that the system is subject to the best possible check when one tries to squeeze as much science as possible out of it. It is expected that this feedback will help to improve and tune the systems before telescope and instruments are offered to the community.

During SV of UT1 the various components of the operations will for the first time work as a single machine, thus making sure the systems work from end to end. This encompasses the technical performance of the telescope, the operations of the data flow and a complete test of all the interfaces in the system. Science Verification should then demonstrate to the community the capabilities of the telescope and its instruments. For community astronomers, SV will deliver data allowing them to assess promptly the suitability of the VLT and its instruments for their own scientific programmes, thus submitting the VLT to a wider scrutiny.

Science Verification will consist of a set of *attractive* scientific observations, so as to involve in the process as many scientists as possible. There will be no restrictions for the data distribution within the ESO member countries. However, observations of the Hubble Deep Field South will be made immediately public world-wide, so as to parallel the release of the HST data.

The telescope SV is planned for August 17–31, which includes new moon (August 21), and will be conducted using the VLT Test Camera. A broad list of possible SV observations was discussed by the scientific management of ESO, and narrowed to a set of higher-priority and second-priority observations. The surviving list (see below) is still meant to oversubscribe the available time, thus allowing the final selection to be done on the spot, depending on the prevailing atmospheric conditions. The observations have been chosen to represent typical imaging applications for an 8-m telescope. However, several technical restrictions (field of view, image scale and CCD characteristics) as well as astronomical constraints (accessible sky) will apply.

This article summarises the planned observations and describes their technical and operational implications. We start first with a summary of the technical aspects of the VLT Test Camera, the instrument with which the telescope is being commissioned and which will be used for SV of UT1. Additional constraints are presented in the next section followed by a brief overview of the calibrations. We end with a description of the scientific goals of the observations.

We invite all astronomers to visit the SV Web site (**http://www.eso.org/vltsv/**) for further information. All SV observation blocks will be available at this Web page, as well as the full text of the SV Plan and of the VLT Test Camera Calibration Plan.

Science Verification has been planned by a small team of astronomers at ESO acting under the overview of the VLT Programme Scientist. The team members are Martin Cullum, Roberto Gilmozzi, Bruno Leibundgut (Team Co-ordinator), Guido de Marchi, Francesco Paresce, Benoit Pirenne, Peter Quinn and Alvio Renzini (VLT Programme Scientist).

The same group, together with the PI of each instrument, will plan the SV for the instruments as well. Science Verification of FORS1 will take place in mid-January 1999, then followed by SV of ISAAC in mid-February, with each SV period consisting of seven nights. The plans for the SV of these instruments will be advertised in the next issues of *The Messenger* and on the SV Web site.

External Constraints

Telescope commissioning will deliver the Cassegrain focus for scientific observations in the middle of August. The SV phase will take place just before the focus will become available for the installation of FORS1. The schedule for the data flow commissioning foresees to provide a functional system at the same time so that SV can be done within the VLT operational paradigms. The data generation from the definition of the observation blocks, which are currently being prepared, to the archiving of the data in the VLT archive will be integral to SV.

The VLT Test Camera

The VLT Test Camera consists of a fully reflective re-imaging system which provides a clean pupil and prevents direct illumination of the detector. The telescope plate scale (1.894″/mm – Cassegrain focus) is maintained. With 24 μm pixels this translates into 0.0455″/pixel. With a thinned, anti-reflection coated Tektronix 2048^2 CCD, this yields a field of view of 93″ on a side at the Cassegrain focus.

The VLT-TC will be equipped with a filter wheel with 7 positions. The filter size and optical parameters are the same as the ones of the SUSI2 camera at the NTT, and the filters can be exchanged between the two instruments. A standard Bessell filter set (UBVRI) has been ordered for the VLT-TC and it is foreseen to add a set of intermediate-band filters suitable for photometric measurements of redshifts. Narrow-band filters will be borrowed from the SUSI2 filter set, if required. Neutral density filters for bright objects are available as well.

TABLE 1: Expected signal for point source objects

(S/N in 1 hour integration)								
magnitude	filters							
	B (seeing)[a]		V (seeing)		R (seeing)		I (seeing)	
	1.0	0.5	1.0	0.5	1.0	0.5	1.0	0.5
22	703	972	503	773	447	744	201	370
23	321	506	217	375	187	341	82	157
24	137	241	90	167	76	146	33	64
25	56	106	36	70	31	60	13	26
26	23	42	15	29	12	24	5.2	10
27	9.1	18	5.8	12	4.9	9.7	2.1	4.2
28	3.6	7.2	2.3	4.6	1.9	3.9	<1	1.7

[a] Seeing in arcseconds FWHM

The shutter of the camera will provide exposure times as short as 0.2 seconds which, with the specified shutter timing, will provide a non-uniformity of 25% between centre and edge of the field. An illumination uniformity of better than 1% is achieved with exposures longer than 5 seconds.

The expected signal for a point source is given in Table 1. The figures have been calculated for an A0 spectrum assuming a dark sky (new moon), two reflections in the telescope, three reflections in the test camera, the Bessell (1990, PASP, 102, 1181) filter transmissions, the CCD efficiency and noise parameters, and two cases of image quality.

The VLT-TC is equipped with a high-quality coronographic capability including an occulting mask located at the UT focal plane to block out light in the core of a bright source and an apodising mask to suppress diffraction at the edges of the aperture and on the spiders. This capability is there in order to carry out precise quantitative measurements of the scattering wings of the UT PSF. The position and slope of these wings carry important information on the scale and power spectrum of the micro imperfections of the primary mirror and on the size and distribution of dust on the mirrors. These wings are the dominant contributors to the extended halos or aureoles around the seeing-dominated core of the PSF which limit the contrast of the VLT even with perfect adaptive optics compensation. This facility will be used to assess the effect of the PSF halo on the precision photometry of faint sources in the presence of brighter objects.

Data Flow Operations

The operations during SV can be carried out fully employing the VLT data-flow system (Silva and Quinn, *The Messenger* 90, 12; Quinn, *The Messenger*, 84, 30). This implies that, as far as possible, all observations will be done with observation blocks (OB). Observation blocks for each observation and the corresponding calibration OBs are prepared in advance. The OB database for SV is the basis for the mid-term and short-term schedules which will be prepared by the SV team for the period of interest and each night according to the atmospheric conditions. OBs for all foreseeable conditions will have to be prepared so that the SV period will be ‘oversubscribed’ by the available OBs to provide a sufficiently large selection pool of observations for any conditions.

The observations and the immediate quality assessment will be performed by the SV team. This includes all calibrations needed for a complete reduction of the data. Science Verification team members in Garching will carry out the data reduction using the data reduction pipeline.

Archiving of the data will be the responsibility of the VLT archive and the SV team will not assume a role here. However, reduced data (e.g. object magnitudes) should be made available through the archive when released by the SV team in Garching.

Boundary Conditions

The sky coverage of the VLT at the end of August will be from RA of 14^h to 7^h. The declination range reaches from the Southern pole all the way to +40°. The accessible sky at the end of August is shown in Figure 1.

For scientifically interesting observations, we have to explore the unique features of the VLT-TC. As a simple imager, the VLT-TC has presumably among the highest throughput of any (imaging) instruments on an 8-m telescope. The reflective optics make the UV wavelength range down to the atmospheric cut-off accessible. The large oversampling of any seeing condition will make the accurate determination of point spread functions possible, which is a pre-requisite for PSF subtraction. For most extended objects and point sources which do not have to be largely oversampled, it will be advantageous to bin the CCD to reduce the effect of readout noise, although, for broad-band filter observations, the VLT-TC will work in the background (sky) limited regime most of the time.

Calibrations

The simplicity of the VLT Test Camera also means that the calibrations are restricted to only a few subsystems. The CCD calibrations will include bias subtraction and (sky and dome) flatfield division. Dark frames will be acquired to check for the dark current. A bad pixel map will be constructed and may be used for some of the observations. Also fringe frames in the case of narrow-band imaging may be required. Other checks for the camera include the CCD linearity and shutter calibrations. We do not anticipate that corrections for these will be necessary, but will acquire the necessary data for control.

Photometric calibration will be achieved through the observation of standard stars. Colour terms for the instrument throughput and second-order extinction coefficients should be established during SV. In the case of narrow-band imaging, we plan to observe spectrophotometric standards to calibrate the filter transmission.

The VLT Test Camera calibration plan gives a detailed description of the planned calibration observations and also describes templates and template parameters. The plan is available at the SV Web site.

Planned Observations

In the following sections the planned science observations are described. They have been sorted into two priority groups. The first set describes the higher-priority observations which will be attempted first. The second group of observations are maintained as backup should the conditions be very favourable. We give here only a very brief account of these observations and refer interested astronomers to the SV Plan available at the SV Web site.

Criteria for the Selection of SV Observations

The following guidelines were adopted for the selection of the observations:

(1) scientific attractiveness,

(2) broad range of “topics” (from Solar-system objects to very high-redshift targets) to ensure involvement of a large fraction of the community,

(3) projects which are generally photon starved,

(4) low-surface brightness objects,

(5) observations which require a large dynamic range,

(6) faint ultra-violet objects,

(7) time-resolved photometry of some very faint objects.

Even with this set of criteria a certain degree of arbitrariness is inevitable, when it comes to the selection of specific targets. We are sure everybody will understand.

Though the VLT image quality is expected to be outstanding among the ground-based telescopes, it makes no sense to attempt using the VLT test camera to compete on image quality with HST.

The observations described in the following section are targeted at representative astronomical objects, but it is not planned to observe complete samples of objects.

During the SV period of UT1 the Galactic plane is accessible for part of the nights, but also a fair fraction of the “extragalactic sky” can be observed (Fig. 1). Three of the four EIS fields and the planned Hubble Deep Field South are also accessible to the VLT during SV. The SV team will run the telescope with flexible scheduling mixing observations of different scientific goals depending on the actual conditions.

Higher-Priority Observations

Hubble Deep Field – South

The HDF-S will be optimally observable in late August, and certainly this field will attract a great deal of follow-up work both from ground and space in the next few years. The SV plan is to observe the STIS field containing the quasar at redshift 2.54 and the two NICMOS fields. Deep imaging of the NICMOS fields in *UBVRI* will complement the near-IR HST data. The quasar will be observed in a narrow-band which isolates objects emit-

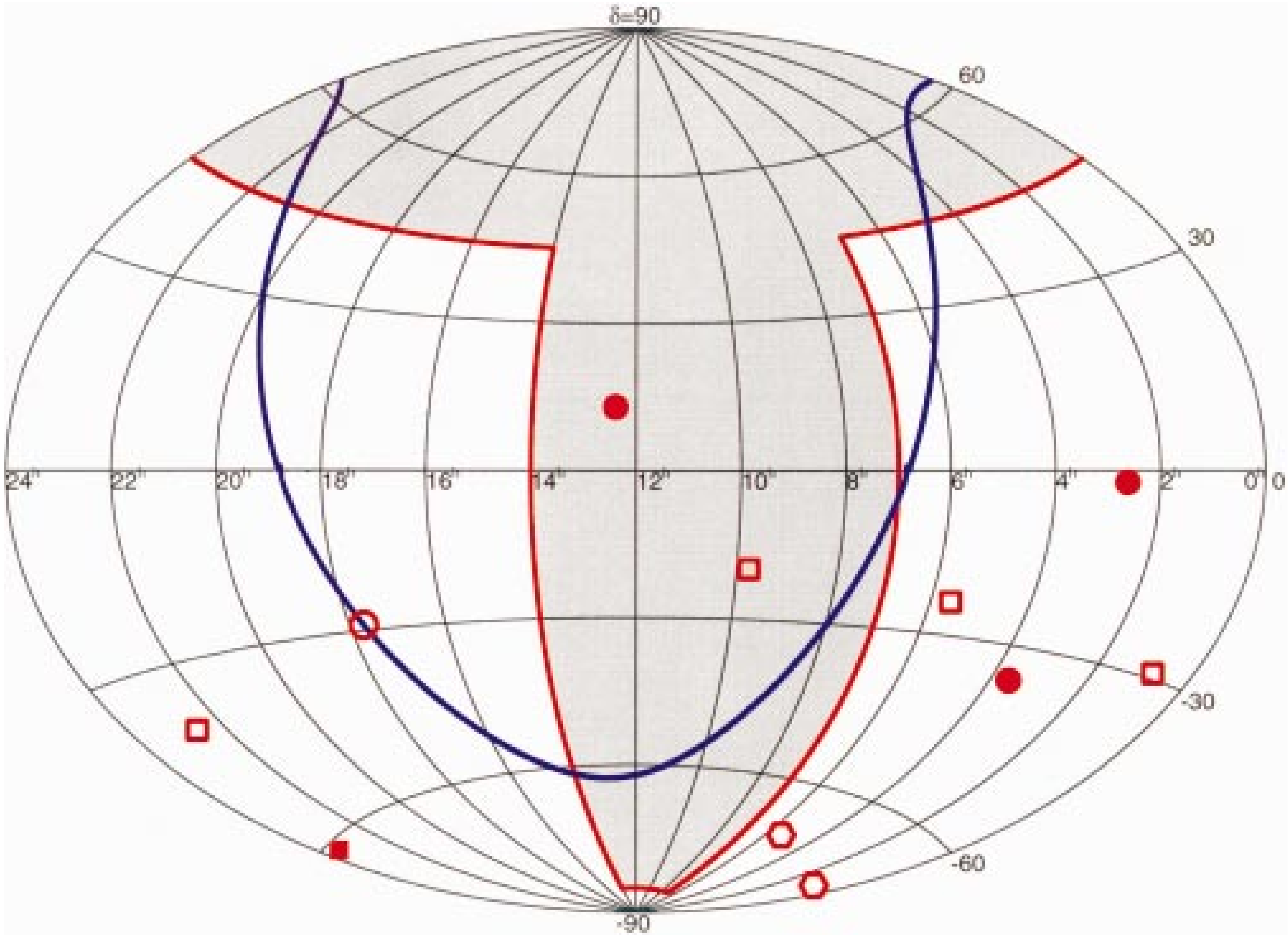

Figure 1: Accessible sky (white area) for SV of UT1 (end of August). The galactic plane is indicated by the thick line. The Galactic Centre(circle), the EIS fields (open squares), position of HDF-S (filled square), the LMC and SMC (hexagons), and the galaxy clusters Virgo, Fornax and Abell 370 (dots) are marked.

ting in Lyα at the QSO redshift to look for companion objects. This will also select candidate objects for spectroscopic redshift observations with FORS1. With somewhat lower priority, one of the WFPC2 fields may also be observed with the SUSI2 set of intermediate band filters.

Detection of the Gravitational Lens responsible for multiply-imaged QSOs

The photon collecting power of the VLT can detect very faint surface-brightness galaxies. The plate scale of the test camera should further provide very good point spread functions for the subtraction of the quasar images. The image quality of the VLT can be readily demonstrated with such observations. The luminosity profiles of the lensing galaxies are fundamental input parameters for the modelling of the lenses.

In order to confirm the presence of the lens, a sequence of co-added VLT Test Camera images, together with the application of powerful deconvolution algorithms, should push the detection limits to considerably fainter magnitudes. A promising object in this category is the optical Einstein ring.

High-z cluster candidates

Mass concentrations can be detected by the effects they have on the light travel through potential wells. An easy way to identify massive clusters of galaxies are the distorted images of background objects (arcs). The ESO Imaging Survey will provide a list of candidate clusters. X-ray selected candidate clusters will also be targeted. Detailed and systematic study (redshifts, structure, galaxy populations, gravitational shear maps, strongly lensed background galaxies at very high redshift, etc.) will certainly form a major set of early VLT projects. Observations in two colours (*V* and *I*) will detect and clearly define the elliptical galaxy sequence in the colour-magnitude diagram. The field of view of the VLT-TC is well matched to the expected size of high-redshift clusters ($\sim 30''$ at $z \simeq 1$). In excellent seeing conditions it should be possible to obtain high S/N shear maps, and detect very high-redshift arcs, if present.

Gamma-Ray Bursters

The optical detection of Gamma-Ray Bursters (GRBs) has opened a new window onto these enigmatic objects. The spectral confirmation of the high-redshift nature of some of these events has been demonstrated. Still, not all GRBs are detected in the optical and their association with distant galaxies has not been shown in every case. Only a small number (< 5) GRBs have been actually detected in the optical. Statistics of the gamma-ray and optical emission will build up very slowly. Deep imaging will provide stronger limits on the optical brightness distribution of the host galaxies of GRBs, if present. A problem with the hosts of GRBs has been their relative faintness. The three cases investigated so far show sub-luminous ($\leq L^*$) objects, which may rule out very massive stars as progenitors of GRBs. Imaging of sites of optically identified GRBs could provide more information on this issue. Should there be a GRB alert during SV with an error box not exceeding the field of view of the VLT-TC, we would certainly attempt an identification and observe its afterglow.

The imaging of a former GRB site is not a problem. Imaging of former sites of GRBs will also prepare the spectroscopic observations by FORS1.

SN 1987A

The shock from the supernova is predicted to reach the inner ring only in the next decade. However, it is starting to ionise material left over by the fast, hot star wind. An HII region inside the ring, i.e. gas ionised by the progenitor Sk –69 201, has been stipulated to be responsible for the observed slow-down of the shock in the radio. X-ray emission is also associated with the shock interaction region. If there are substantial amounts of ionised gas inside the ring, it should be at very low surface brightness. It still has not been detected conclusively. Narrow-band imaging in Hα and [O III] is the best chance to see this emission with the VLT. STIS has detected high-velocity Lyα from inside the ring. The ring itself has started to brighten in a single spot. So far it is undecided whether this brightening is due to changing ionisation or an early interaction of material which did not suffer any braking by shocks.

UV imaging of HST fields in globular clusters

One of the most intriguing, yet most interesting aspects of globular cluster dynamics is the fate of these systems after core collapse. While it is today demonstrated, on solid theoretical grounds, that they all must undergo this catastrophic phase on a timescale of order $\sim$ 10 Gyr, it is still not at all clear how the stellar population in their cores would react to strong densities (up to $\sim 10^9\ M_\odot\ pc^{-3}$) such as those expected to accompany the gravothermal instability. Coupled with the relatively low velocity dispersion of the stars in the core, such an extremely high density sets the ideal conditions for the formation of hard binaries, which will eventually heat the cluster core. Close binary systems and cataclysmic variables are, therefore, expected to play a dominant role in the post-collapse evolution of clusters, and should populate in large amounts the densest cores which are at higher risk of collapse.

Although only a few cataclysmic binary systems have so far been detected in globular clusters from the ground, a random and sporadic search for blue variable objects in globular cluster cores conducted with HST has already turned up quite a good number of interacting binaries. While no ground-based instrument can achieve the spatial resolution needed to peer deep into the cores of dense clusters, the collecting area of the VLT and the good near-UV sensitivity of the VLT-TC, coupled with the astrometric information of the available HST data, can serve this job by allowing us to locate all the variables in the cores and to obtain a good light curve of the objects having a period in the 2–10 hr range as might be expected from most interacting and eclipsing systems. We will then be able to evaluate observationally the influence of these binaries on the dynamical evolution of the clusters. Images will be analysed with a restoration technique which makes use of high-resolution astrometric information to reach high-quality photometry of stellar objects in ground-based crowded fields.

Timing of Pulsars

The first pulsar detected in γ-rays, Geminga (PSR J0633+1746), is one of the most mysterious objects in the sky. Its parallax and proper motion have been measured and its luminosity has been obtained at various wavelengths. It carries all signatures of an isolated cooling neutron star. The period derivative measured in the γ-rays suggests an age of about 3.4×10^5 years, typical of a fairly settled object. Geminga has been observed as a faint optical source at $B \simeq 26.5$. Recently, optical pulses have been reported from this object. Already five pulsars have data on optical pulses, all with photon-counting devices. The VLT-TC should be able to detect the optical pulses of some of these objects as well. The pulse measurement can be achieved by repeated integrations while moving the charge on the CCD. Since the pulse period is known very accurately from observations at other wavelengths, we can move the image on the CCD at this period and detect the pulse shape and any thermal, inter-pulse emission.

Lower-priority observations

Giant arcs in clusters

Through the amplification of the light by gravitational lenses, we are able to examine faint objects at larger distances in the Universe than allowed by other techniques. Observations of lensed galaxies can provide important new insights into their formation and chemical evolution as well as clarify when in time these processes took place. Broad-band observations of distorted galaxies have been used to infer the redshift distribution to R = 27. Since the asymmetry is best observed at the faint, outer isophotes, the VLT can significantly increase the S/N.

Quasar host and companion galaxies

The intense radiation emitted by QSOs must have a significant impact on their host galaxies. Very few host galaxies of quasars have been observed so far because of the strong contrast between the luminosity of the galaxy and that of the QSO. The morphologies of these objects span all known galaxy types including disturbed systems. Since, however, no colour information is available to date, the current star-formation rate or its history remain still unexplored. Detecting host galaxies of quasars and determining their accurate colours through broad-band imaging can teach us about the influence of the central power house on the surrounding material.

The large brightness contrast between the bright nuclear region and the galaxy requires a large photon-collecting power and small pixel sizes so as not to saturate the point source, yet still reveal the comparatively faint surface brightness host.

Proper motion projects: Trans-Neptunian objects

The current inventory of the outer Solar System includes about 50 Trans-Neptunian objects (TNOs), whose orbit semi-major axis is in the 30–45 AU range, 7 Centaurs, orbiting between Saturn and Neptune, and many Short-Period and Long Period Comets (SP and LP respectively, a few hundred in total).

The dynamical studies and theoretical models of these populations link their formation to different regions of the Solar System: while the LP comets were formed in the Jupiter-Saturn region, then ejected by these planets to the outer Solar System, forming the Oort Cloud(s), the SP comet would have formed *in situ*, together with the TNOs, in 30–150 AU ecliptic region, forming the Kuiper Belt. The scattering of some of these comets and TNOs by the planets caused them to migrate on to larger orbits. The outward migration of Neptune caused its accompanying orbital resonance to sweep a broad region of the inner Kuiper belt, and explains the observed eccentricity distribution of the observed TNOs. The major problem is that these models need observational support: for most of the TNOs discovered, the only magnitude available is a crude estimate made from the discovery image, and only a few have colour measurements. About a dozen of short-period comets and a couple of the Centaurs have been measured.

With projected proper motions in the range of a few arcsec per hour and magnitudes around $V \simeq 23$–26 for a typical TNO, several short exposures will have to be collected for each object in order to minimise tracking problems. Candidates are available around the ecliptic, however, there is a concentration near 0^h and 12^h RA due to selection effects (low star density).

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