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VLT Science Verification Plan

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Contents

1 Introduction

It is the goal of the VLT Science Verification (SV) to provide the community with the earliest scientific return possible. It further verifies that the VLT is fully understood and provides tested telescopes and instruments. Therefore, after the commissioning period, a set of typical scientific observations should verify and demonstrate to the community and the public at large the scientific capabilities of the telescopes and of the instruments in the operational frame of the VLT Observatory. To this end, during SV the correct interplay between the various hardware and software systems under the VLT operational paradigm will be checked with representative science observations. For community astronomers, SV will deliver data allowing them to assess promptly the suitability of the VLT and its instruments for their scientific programs, thus submitting the VLT to a wider scrutiny. Astronomers in the community will be approached and encouraged to analyze the SV data as quickly as possible and feedback their experience to ESO. This document deals with the Science Verification of UT1. Similar documents will describe the SV of each individual VLT instrument.

1.1 Scope

Commissioning of a VLT unit telescope will deliver a fully functional and technically tested telescope. Before the first instruments will be installed on the telescope its actual scientific performance shall be demonstrated by a series of scientific observations which will make use of the VLT Test Camera (VLT-TC). During this SV phase, astronomers will assess the capabilities and limitations of the telescope.

1.2 Purpose

During SV the telescope will not be tested for particular technical aspects as was done in commissioning, but rather its scientific performance will be demonstrated. To this end, no technical specifications will be tested, but SV will show whether the VLT can achieve the scientific goals which are defined in this document. SV will also determine observational parameters like the sky brightness and extinction coefficients at Paranal.

1.3 Reference Documents

-[1]- Commissioning Plan (VLT-PLA-ESO-10000-0937)

-[2]- VLT Science Operations Plan (VLT-PLA-ESO-10000-0441/2.0)

-[3]- VLT Test Camera - Technical Specification (VLT-SPE-ESO-11960-0839)

-[4]- VLT Test Camera - Calibration Plan (VLT-PLA-ESO-11960-1517)

-[5]- Test Report on Tektronix TK2048EB 1522BR07-01 (19. January 1996)

1.4 SV Team

The SV team is composed of people involved in all aspects of the VLT observatory. All main functions are represented by at least one person. The astronomical observations and reductions of SV are prepared and managed by the SV team. Any analysis required to fully describe and interpret the data will also be part of the SV work. However, the SV team will not perform a scientific interpretation of the data, but organise collaborations in the astronomical community.

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B. Pirenne — ECF, HST, Archive
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1.5 Involvement of the community

Involvement of the ESO community is a crucial ingredient of SV, Messenger articles and an SV Web page shall inform the community of the plans for SV and describe the observations in some detail, and the SV data will be available to the community immediately. This should ensure an early exposure of astronomers to VLT data, allowing them to directly assess the performance of the telescope and better plan for their own research with the VLT. SV data will have intrinsic scientific value and and their scientific interpretation will be coordinated and encouraged. Attempts will be made to identify concerned researchers in the ESO community, and the SV team will urge them to participate in the effort and provide prompt feedback.

The SV Observation Blocks (OB) will be made accessible on the Web page so that astronomers can get acquainted with the OB concept and VLT science data flow.

1.6 Overview

The current VLT schedule (version 15) foresees the SV of UT1 to take place between 17.–31. August 1998. SV with the VLT-TC shall include at least one dark period (two weeks around new moon) to ensure that the scientific capabilities of the telescope can be tested with an optical imager. At the time of SV the corresponding focus of the telescope should be fully commissioned. This is expected to the be Cassegrain focus. This includes automated image analysis and active optics loops.

During SV several members of the SV team will be present on Paranal to prepare and run the observations. The telescope and the instrument will be operated by the Telescope and Instrument Operators (TIO) who are working in the regular turno system. Their training should be completed with commissioning, and SV will be the first practical VLT science observing experience for these people. Paranal Observatory staff will be at hand for regular maintenance activities (refilling of dewars, filter changes, etc.).

The quality of the observations will be assessed by SV team members on Paranal and includes the check of the image quality, meteorological condition (photometry), and moon phase. Data reduction is done by SV team members in Garching during the next day. The raw as well as any calibrations and reduced data will then be entered into the public VLT archive in Garching and distributed to interested groups of astronomers in the ESO community, which will be urged to report back to the SV team about the results of their own analyses.

All data will become public without any proprietary period after the observations. Conflicts with observing programs from the community for VLT instruments are not anticipated given the nature of the VLT-TC. The SV observations shall be optimized for an 8m telescope and it is not expected that they will overlap with current programs at La Silla telescopes. The final selection of the observations is done by the VLT Programme Scientist (see also SV Policy statement in Appendix A).

Feedback to the commissioning team is given in cases where performance problems are encountered or suspected. Should the telescope not perform nominally it will be returned to the commissioning team for detailed investigation and problem resolution.

The following sections describe the external boundary conditions on SV (§2) including the guidelines for the selection of scientific observations envisaged for SV, the calibrations required (§3), a description of the planned observations (§4), and a summary of the actions needed for preparations and successful completion of SV on UT1.

2 SV Environment

This section describes the environment in which SV will take place. Science Verification of the telescopes will employ the simple imager which is used for the telescope commissioning: the VLT Test Camera [3]. SV will be done under the VLT operations paradigms and with the tools of the Data Flow System [2], including observation blocks. For rapid distribution, the data will have to be ingested into the VLT archive. Science Verification is the first time when the operations and all modules of the VLT observatory will run in a regular manner. It, thus, provides an end-to-end test of the observatory including the data flow operations. Any improvements and tuning of the system can then be achieved before instruments come to the telescope and regular community use begins.

SV will rely on a functioning Astronomical Site Monitor for a real-time assessment of seeing and wind conditions. Forecasting of cloud cover and temperatures shall be available for the planning of flexible scheduling and the telescope seeing management.

2.1 The VLT Test Camera

The specifications of the VLT-TC are summarized in [3]. Of particular interest for SV are the pixel size, the field of view, CCD parameters (sensitivity, readout noise, gain), and overall sensitivity of the system.

The VLT-TC consists of a 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 24μm pixels this translates into 0.0455$''$/pixel with slight deviations due to the exact shape of M1 under adaptive optics. With the 2048^2 Tektronix CCD (TK2048EB Serial number:1522BR07-01) this yields a field of view of 93$''$ on a side.

The measured sensitivity of the CCD [5] is given in Table 1. The CCD electronics will be the FIERA controller. The expected readout time of the full, un-binned CCD is $\sim$15 seconds ($\sim$60 seconds through 1 port) with a readnoise of $<$10 e^-. The optimal gain setting for the observations will have to be chosen with FIERA.

Table 2 summarizes count rates for a sky brightness of the dark (new moon) and bright (full moon) sky as measured at the Cerro Tololo Inter-American Observatory (NOAO Newsletter Nr. 37, p. 29 - as used in the SUSI Manual). It is clear that there will be no problem with the sky background for any reasonable integration times with the VLT-TC. The table also specifies the integration time at which the photon statistics from the sky background start to exceed the readout noise of the CCD. Exposures with integration

Table 1: Measured quantum efficiency of the VLT-TC CCD

wavelength (μm)	efficiency (%)	comments
320	24	atmospheric cutoff
340	33	
360	44	
380	55	
400	65	
450	64	
500	68	
550	72	
600	75	
650	77	
700	78	
750	71	
800	65	
850	52	
900	37	
950	24	
1000	11	

Table 2: Expected sky flux and CCD count rates per pixel

	dark sky			bright sky		
filter	sky brightness mag arcsec^{-2}	flux e^{-} s^{-1} pix^{-1}	time(bkg) s	sky brightness mag arcsec^{-2}	flux e^{-} s^{-1} pix^{-1}	time(bkg) s
U	22.0	0.06	>3600	17.0	4.6	22
B	22.7	0.49	210	19.5	11	9
V	21.8	0.95	110	20.0	5.0	20
R	20.9	2.5	40	19.9	6.7	15
I	19.9	3.7	30	19.2	7.1	14

times longer than t(bkg) can be coadded without increasing the CCD related noise.

Table 3 shows the predicted integration times and signal to noise ratios for a set of point source magnitudes (A0 star spectrum) assuming a total telescope reflectivity of 81% (two mirrors at 90%). Table 4 gives surface brightness magnitude values for a dark sky (new moon). Since for the surface brightness objects the spatial resolution of objects is less critical, it is likely that the CCD will be binned in these instances which means that the S/N will increase approximately linearly with the binning. Thus, by binning the CCD 3×3 we would increase the S/N per pixel by a factor of about 3.

The VLT-TC will be equipped with a filter wheel with 7 positions. The filter size and optical parameters are the same as the one of the SUSI 2 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 SUSI 2 filter set, if required. Neutral density filters for bright objects are available as well.

Table 3: Expected signal for point source objects
(S/N in 1 hour integration)

magnitude	filters							
	B		V		R		I	
	(seeing)[a]		(seeing)		(seeing)		(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
29	1.5	2.9	<1	1.8	<1	1.5	<1	<1
30	<1	1.2	<1	<1	<1	<1	<1	<1

[a] Seeing in arcseconds FWHM

Table 4: Expected signal for surface brightness objects
(S/N per pixel in 1 hour integration)

surface brightness (mag arcsec^{-2})	U	B	V	R	I
18.0	101	355	325	365	249
19.0	62	221	200	221	141
20.0	36	136	119	127	73
21.0	20	80	67	66	34
22.0	9.7	44	34	32	15
23.0	4.3	22	15	14	6.1
23.5	2.8	15	10	8.9	3.9
24.0	1.8	10	6.7	5.7	2.5
24.5	1.2	7	4.3	3.7	1.6
25.0	0.7	4	2.8	2.3	1.0
25.5	0.5	3	1.8	1.5	0.6
26.0	0.3	2	1.1	0.9	0.4
26.5	0.2	1	0.7	0.6	0.3
27.0	0.1	0.7	0.4	0.4	0.2

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 center and edge of the field. An illumination difference of less than 1% is achieved by exposures longer than 5 seconds.

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 apodizing 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 that limit the contrast of the VLT even with perfect AO compensation. This facility will be used to assess the effect of the PSF halo on the precision of photometry of faint sources in the presence of brighter ones.

In addition the large imaging CCD the VLT-TC is masked to provide two small areas with which stars can be tracked.

Part B of the CCD camera will hold two large format technical CCDs which are used during the telescope commissioning. They will be available for SV if programs required a larger, although not continuously sampled, field.

2.2 Data Flow Operations

The operations during SV can be fully within the VLT data flow system. This implies that, as far as possible, all observations will be done with observation blocks (OB). Only a few highly specific observation techniques which will not be supported by templates will have to be run directly from the OS panels. Observation blocks (OB) or sequences and setup files 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 scheduling program for the efficient selection of the observations should also be available.

The observations and the immediate quality assessment will be done by the SV team. This includes all calibrations needed for a complete reduction of the data. SV team members in Garching will perform the data reduction, possibly using the data reduction pipeline, as soon as possible (goal: next day). Should SV last for 14 days the Paranal SV observing team (at least two people) may do all the observing. Should SV last longer more observers for a shift system have to be planned. There will always be at least two SV team observers present at Paranal during SV.

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

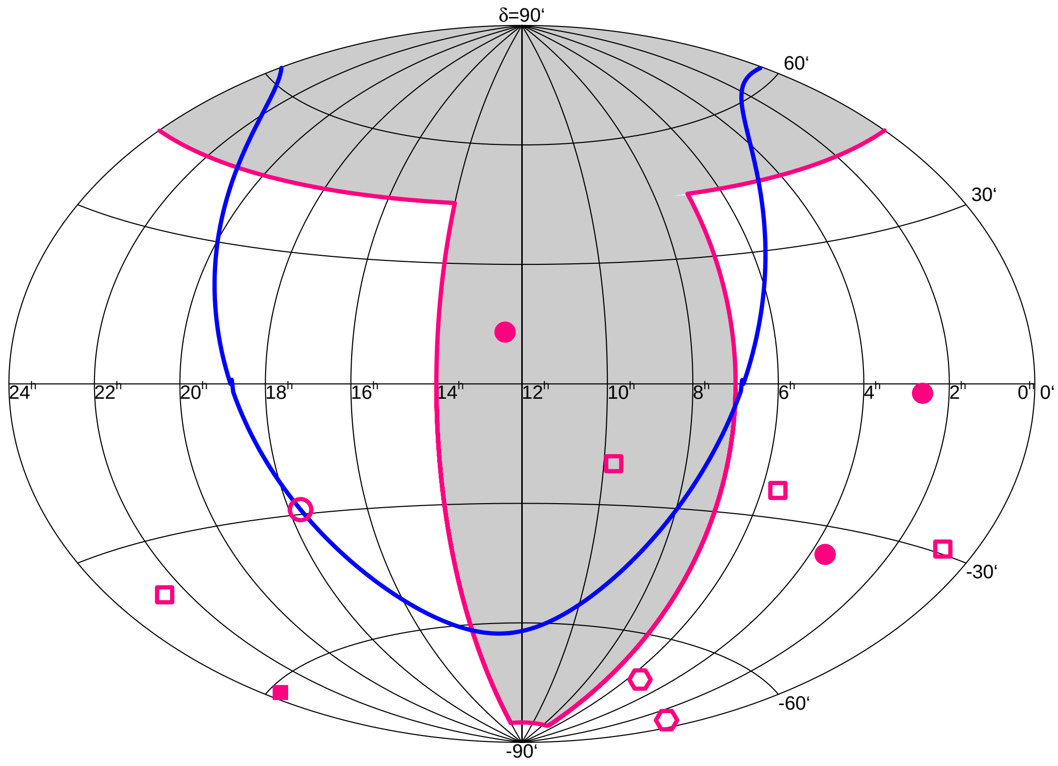

Figure 1: Accessible sky for SV of UT1 (end of August). The galactic plane is indicated by the thick line. The Galactic Center (circle), the EIS fields (open squares), planned position of HDF-S (filled square), the LMC and SMC (hexagons), and the galaxy clusters Virgo, Fornax and Abell 370 (dots) are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

2.3 Boundary Conditions

The sky coverage of the VLT at the end of August will be 14h $<$ RA $<$ 7h. 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. The RA limits increase by +2 hours per month. Targets will be selected in the above sky region, but a set with later RA will also be prepared.

An important quantity of all exposure time calculators is the sky brightness of a site and the photometric parameters (extinction coefficients). The VLT-TC will be used during SV to determine the sky brightness at Paranal and the second order extinction coefficient which changes very little over time.

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 8m telescope. The reflective optics make the UV wavelength range down to the atmospheric cutoff 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 don't 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 (Table 2).

2.4 Criteria for the Selection of SV Observations

To provide fully competitive data, SV will concentrate on imaging programs which are photon starved. Any program which on 4m telescopes requires unreasonably long exposure times to beat the CCD readnoise and the photon shot noise from the sky (cf. Table 2) are prime targets for VLT SV. It would also be wise to avoid trying to compete with HST on image quality. The most obvious programs involve low surface brightness objects, time-resolved photometry of short-period, faint targets, emission line imaging, crowded fields with high dynamic range, and the faint UV objects which can not easily be accessed with smaller telescopes. The selection of SV programs has been concentrated on the above-mentioned classes of objects.

The input to the SV program catalog has been assembled from various sources. The Hubble Deep Field South has a comparable field size to the VLT-TC. By observing the same field to a similar limiting magnitude the VLT can contribute the faint surface brightness objects, and the extent of the brighter objects detected by HST. Another possibility are observations in intermediate-band filters which could refine photometric redshift estimates.

The observations described in the following are targeted at typical representatives of astronomical objects. This means that for each observation there should be several targets accessible during the SV phase. It is, however, not planned to observe complete or even representative samples of objects as SV should serve as many astronomical topics and test as many different observing techniques as possible in the limited time allocated.

The Galactic plane is accessible part of the nights but also a fair fraction of the extragalactic sky can be observed (Fig. 1). The Galactic Bulge is an early evening object. Three of the four EIS fields and the planned Hubble Deep Field South are accessible to the VLT during SV. The Magellanic Clouds are also visible towards the end of the nights. For combination with FORS and ISAAC SV (planned for January and March 1999, respectively) fields near the end of the night should be considered.

The SV team will run the telescope with flexible scheduling mixing observations of different scientific goals depending on the actual conditions.

SV will take over the telescope from the commissioning team after completion of commissioning. There may be observations during commissioning which might be done on scientifically interesting targets, although they serve a technical aspect. The commissioning team can access the SV observations pool for such exposures and will be supported by the SV team in reductions and quality control. Some of those data may enter the archive after decision by the Director General.

3 Calibrations

3.1 CCD Calibrations

CCD calibrations have evolved to a fairly standard format over the last few years (e.g. 'User's Guide to CCD Reductions with IRAF' by P. Massey, 15. February 1997). What is needed are the corrections for the detector and detector controller noise introduced in the data. The following calibration data will have to be acquired for any gain setting, CCD binning, windowing, and amplifier used: determination of bias level, dark current, pixel-to-pixel variations, bad pixels, and, possibly, fringe frames.

The following paragraphs describe the accuracy the calibrations should achieve and present preliminary values for the number of exposures needed (see also [4]). The exact numbers will be defined once the characteristics of the CCD are known.

3.1.1 Bias Frames

The calibrations of the VLT-TC CCD will include regular bias frames. The noise contribution of the combined bias frame should be below 1% (RMS) per pixel which is normally achieved by combining about 20 individual bias frames (assuming an RMS noise of $7e^-$, a bias level of 250 counts, and gain $\sim$1). Note that the bias level changes very little as long as the gain setting or CCD amplifiers are not changed. To remove any cosmic rays it is necessary to coadd several bias frames. This requirement is redundant since a series of bias frames is needed for the noise reduction anyway. Bias frames should be obtained for every night the specific configuration is used (typically in the preceding afternoon or the following morning).

3.1.2 Dark Frames

The dark current of most CCDs has become a negligible quantity. Nevertheless, we plan to obtain a set of dark frames to measure the dark current (for each CCD configuration used to acquire science data). This is done to ensure that we do not have to worry about any significant contribution to the noise. The specification of the VLT-TC asks for a dark current of $<$10 e^- pixel^{-1} hour^{-1}. With a set of about 5 dark frames each of 1 hour duration per week the determination of the dark current and its stability can safely be established. The dark current should not exceed the readout noise in a 1 hour exposure. Should the subtraction of the dark frames become necessary, we will combine all dark frames to a master dark and subtract this frame from the data. Multiple dark frames are required for an efficient removal of cosmic rays.

Note: Dark frames will have been obtained during commissioning and the stability of the system will be known to a fair degree. SV can make us of those data should darks not be available immediately.

The dark frames further provide a means to find and characterize “hot” and “warm” pixels. This information will be used for specific analysis purposes, but not be implemented into a regular pipeline. In general, these irregularities are not important for imaging and broad-band photometry. In situations, where the counts in the “hot” pixel is of the order of the background counts special care in the reductions may have to be taken. These cases, however, are most likely be dealt with by the bad pixel mask (see below).

3.1.3 Flatfield Frames

The pixel-to-pixel variation depends on the wavelength and has to be established for each filter individually. It can be determined reliably by exposures to the light of a lamp in the dome (dome flats) for narrow- and intermediate-band filters where the wavelength range is fairly restricted and the influence of the wavelength dependence of the pixel response is limited. **Note: At the time of writing the situation concerning dome flats is unclear. Will a large enough screen be provided for dome flats? Can dome flats be done off the blank (shutter) walls?** For broad-band filters it becomes important to match the color of the object as closely as possible. This can be achieved with twilight flats or, should there be a screen which can be uniformly illuminated by scattered sunlight, through dome flats. The latter method has the problem that the color of the sun does not exactly correspond to the color of the night sky and twilight flat fields are preferred. In some cases flatfields can be constructed from regular science exposures, if they have background flux dominating the readout noise (typically broad-band filter images only). By combining a large number of deep science frames with non-extended sources good flatfield images can be constructed. This requires that targets are placed on different locations on the CCD. This approach is unlikely to be useful for the VLT-TC due to the large PSF. It may, however, be necessary to obtain "dark" sky images to match the color of the sky as accurately as possible. There will be no "blank" fields for the VLT and a careful offsetting between exposures has to be considered. This calibration should be done only in special cases where the observations depend on such an accurate color match.

The noise contribution of the flatfields should not exceed 1% per pixel which implies that they require an exposure level of at least 10000 e^-. This is very easily achieved even in a single integration. Note, however, that at least three (better five) exposures for each setup are required to efficiently remove cosmic rays.

Flatfield frames should be obtained preceding or following any night the filter has been used for science observations. This is to remove any irregularities which may arise from dust on the dewar window or the filters themselves. Such dust particles can move during a night and can create flatfielding errors of a few percent depending on the illumination.

3.1.4 Bad Pixel Mask

Non-linearities in CCD pixels can occur and some chips also contain blocked columns which affect the data. For many applications these defects are purely cosmetic and can be safely ignored. We will create a bad pixel map during SV (also to compare with any obtained during commissioning). To construct the bad pixel map low level flatfields ($\sim$100 e^-/pixel), in combination with any high-level flatfield frames (3.1.3), are needed. The noise of the combined low level flatfields should be less than 2% which implies at least 10 individual exposures. The bad pixels are interpolated from neighboring pixels in the reductions and thus the exact value of the non-linearity is not required.

3.1.5 Fringe Frames

Fringe patterns from narrow-band filters are stable and can be removed by the regular flatfielding.

For broad-band imaging in the near-IR ($\lambda > 8000\mathring{A}$) the narrow night sky lines produce fringes in the CCD. The strength of the night sky lines varies on a time scale of minutes to hours. Thus the fringes in science exposures vary to some degree. Depending on the illumination the fringes also move on the frame and their removal is fairly difficult. Special fringe frames (deep sky frames) have to be obtained for this purpose. The signal in the sky has to be high enough in order not to introduce additional noise when defringing the science frames. It is not planned to obtain fringe frames on a regular basis as very few observations depend on the accurate removal of the small (amplitude typically about <5% on current chips) non-uniformity. Only observations which have objects of a similar spatial scale and signal may need defringing.

3.1.6 CCD Linearity

Apart from the simple linearity check for the production of the bad pixel mask we will not determine deviations from linearity of the CCD in SV. We assume that this test has been performed previous to SV by the ODT [5].

3.2 Instrument Calibrations

The VLT-TC is a very simple instrument with very few functions relevant for SV. We restrict the discussion of the instrument calibrations to the shutter and the coronographic mode. The measurement of the color term of the system will be described in section 3.3.

3.2.1 Shutter calibrations

For accurate photometry it is important to measure the illumination variations introduced by the shutter. Also any shutter delays have to be known. For most VLT instruments these will be critical parameters as the observations of (bright) standard stars will often require short exposure times.

The shutter delay and illumination map will be created by a series of exposures with increasing (or decreasing) exposure times. The last exposure in the series will have the same integration time as the first one to detect any possible drifts in the illuminating source. The shutter delay and timing will be determined with these data.

Once the integrations become long enough that the shutter timing becomes negligible the data measure the linearity of the CCD. With an appropriate choice of integration times this calibration can be combined with the CCD linearity calibration (see 3.1.6).

The SV team will obtain a shutter map once during the SV period.

3.3 Photometric Calibrations

Photometry depends on the condition in the atmosphere as well as the color sensitivity of the telescope-instrument combination. To establish these calibrations observations of standard stars during the night are required. The color term of the instrument (which also includes the telescope) is stable as long as there are no major changes in the system (CCD changes, re-aluminization of mirrors, filter swaps, etc.). The second order extinction coefficient is also varying very little over time (except when major changes in the upper atmosphere occur, e.g. dust deposited by major volcano explosions). The first order extinction coefficient on the other hand changes from night to night.

For broad-band photometry the method of Harris et al. (1981, PASP, 93, 507) combines standard star observations of several nights to determine the slowly-changing color term and second order extinction using the complete data set while simultaneously solving for the first-order extinction of each night individually. We will make use of this method to measure the extinction and the color terms. The minimum requirement for a good determination of the first-order extinction are about 30 standard star observations in each filter for which science observations are obtained during the same night. Note that they have to be distributed over a range of colors and airmasses which spans all science observations. With suitably chosen standard star fields several standard stars can be observed at the same time thus reducing the number of standard star exposures. The latter have to be scattered throughout the night to detect temporal changes, if present.

Doubtful nights typically require more standard star observations to track the evolution than impeccable nights.

Narrow-band photometry relies on the observation of spectrophotometric standards to determine the exact sensitivity at the given wavelength range. The extinction has to be determined in the same way as with broad-band photometry. Since spectrophotometric standard stars are normally isolated they have to be observed one by one.

4 Higher priority 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 should be attempted first. The second group of observations are maintained as backup should the conditions be very favorable.

4.1 High-z cluster candidates

4.1.1 Rationale

EIS will provide several candidate clusters at moderate to high redshift. According to current projections of the EIS Team the catalog of candidate clusters will be released to the public on July 31, 1998, and will contain about 300 such candidates, with z up to ~ 1 or slightly beyond. On EIS images tentative redshifts are estimated by a matched filter technique that uses both the luminosity function of the excess galaxy counts and their radial distribution. It is estimated that $\sim 50\%$ of the candidates will turn out to be real clusters, the others being just chance alignements or statistical fluctuations. The identification of the real clusters and their 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 that the ESO community will start applying to from Period 63 onward. However, a pilot SV Test Camera imaging program should be very useful and scientifically attractive for several reasons. Observations in two colors (e.g. V and I) will detect and clearly define the elliptical galaxy sequence in the color-magnitude diagram, which is known to be rather sharp out to at least $z = 1$. The detection of such a feature will allow to confirm the reality of the cluster as well as to estimate its "photometric redshift". Gravitational shear maps on the same images will further confirm the reality of clusters, and provide a first estimate of their mass and mass distribution. Finally, some of the clusters may contain one or more very red arcs, i.e. very high redshift $z > 4$ galaxies that are lensed by the cluster.

4.1.2 Technical Issues

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 very high S/N shear maps, and detect very high redshift arcs, if present.

4.1.3 Scientific Testing

The construction of shear maps will require to push the control of field distorsions to the limit.

4.1.4 Risks and Opportunities

Some of the candidate clusters will not be confirmed as such, hence the corresponding images will be of rather limited interest. However, there is a chance to detect very high redshift arcs, some of which might be at $z > 5$. Spectroscopic follow up of such arcs during FORS1 science verification may lead to important discoveries.

4.1.5 Publicity and Press Releases

These observation may set stringent limits on the epoch of elliptical galaxy formation, provide estimates of the mass of high redshift clusters, and perhaps allow the discovery of most distant objects, all issues being quite attractive for PR releases.

4.2 Photometric redshifts in the HDF-S

4.2.1 Rationale

It is expected that the HST will be used once again for deep imaging of an extragalactic field (known as Hubble Deep Field; Williams et al. 1997), yet this time in the southern hemisphere. The northern deep field has yielded a wealth of information on distant galaxies and clusters. However, the redshift distribution of the objects in the field has shown to be essential in characterizing the evolutionary state of each galaxy. While spectroscopic redshifts can be measured with an instrument such as FORS, there is also the possibility of getting statistical redshifts from the color properties of the galaxies. With an appropriately designed set of intermediate-band filters, the redshift distribution can be obtained with fair accuracy, even for those objects which are too faint for spectroscopy. In this way, it will be possible to extend redshift determinations to more distant galaxies, thus increasing the redshift range, and to investigate the properties of faint galaxies. By observing the STIS field, which includes the $z = 2.54$ QSO, and the NICMOS fields the VLTTC can provide complementary imaging data.

4.2.2 Technical Issues

The field of view of the VLT-TC matches that of a single chip of the WFPC2 almost exactly. No binning will be adopted, in order to preserve the highest angular resolution possible and thus accurately sample the PSF, which is a key issue in this program. This will not limit the surface brightness measurement as the observations will be mostly sky limited anyway. The UV sensitivity of VLT-TC will put this instrument at an advantage with respect to the WFPC2. A set of medium band filters will have to be used. Filters will have to be properly calibrated through the observation of photometric and spectrophotometric standard stars, which will also provide the extinction coefficients.

4.2.3 Scientific Testing

This program would allow us to test the photometric speed of the VLT-TC setup as well as the telescope tracking stability.

4.2.4 Risks and Opportunities

Simple imaging, no risks anticipated. The photometric redshifts will be the first redshifts available in the field and possibly provide the best candidates for a spectroscopic confirmation with FORS.

4.2.5 Publicity and Press Releases

The photometric redshifts potentially can reveal objects out to $z = 5$ and maybe beyond. Although such claims in the HDF-North have not been generally accepted, they are not based on suitable filters. The proposed SV observations could potentially find some of the most distant known objects in the universe.

4.3 Detection of the Gravitational Lens responsible for the multiply-imaged QSO J03.13

4.3.1 Rationale

Multiply-imaged quasars have been studied with great vigor for over 15 years. Their study has provided a new way to look at the high-z Universe. The nature of the phenomenon itself is also worth studying. A real challenge is a direct detection of the lens responsible for the deflection of the light rays. It then becomes possible to properly model the gravitational lens systems and use them as astrophysical and cosmological tools.

J03.13 is a multiply-imaged, lensed QSO primarily detected from (unresolved) direct CCD images taken with the ESO/MPI 2.2m telescope (Claeskens et al. 1996). Further HST imaging and spectroscopy of the object's components (separation 0.849") have confirmed the $z = 2.545$ doubly-imaged nature of J03.13 (Surdej et al. 1997). However, the lack of photon collecting power of HST has not allowed the direct detection of the lens. It is very likely to be a faint, red galaxy at $z = 1.085$ causing absorption in both quasar spectra.

In order to confirm the presence of the lens, a sequence of co-added VLT Test Camera images, together with the application of novel, powerful deconvolution algorithms (Lucy-Hook 1998), should push the detection limits by a large factor.

The presence of absorption systems in both component spectra at $z = 1.085$, very likely associated with the lens, calls for a challenging detection work. It should be located within the two QSO images separated by $0.85''$. The good seeing at Paranal, optical quality and much better low surface-brightness response of the VLT (8m telescope) should bring the lens in within reach.

Another object in this category is the optical Einstein ring reported by Warren et al. (1996). The faint surface brightness of this object could be suitably tested.

4.3.2 Technical Issues

The demands on the image quality are considerable. These observations would test the capabilities of the telescope to maintain an excellent focus for an extended period.

4.3.3 Scientific Test

Detection of LSB galaxies at $z = 1$, the galaxy being embedded in the light of a bright quasar. Both excellent angular resolution and collecting power of a large telescope are mandatory for the detection of the lens.

4.3.4 Publicity and Press Releases

Direct view of a high z (1.085) lens of a gravitationnally brightened quasar. The image of the Einstein ring would be rather spectacular.

4.4 Gamma Ray Bursters

4.4.1 Rationale

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 two cases investigated so far show sub-luminous ($< L^{\star}$) objects, which would 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.

4.4.2 Technical Issues

The candidate objects would be observed in V, R, and I to obtain color information down to about R=26. The observations will be straight forward imaging and do not provide any technical problems. The data flow will have to be flexible enough to accommodate the target of opportunity on a short time scale (<1 hour). This should easily be possible with the current system. Any ToO would be a good test of the flexibility of observations at the VLT.

We should attempt to image the field of an optically identified GRB to check for any host galaxies. Compared to the HST, the VLT could detect faint low-surface brightness regions.

4.4.3 Scientific Testing

For a conclusive optical identification of a GRB the brightness change over several hours will have to be detected. This requires a high photometric stability of the system (possibly also the PSF for the subtraction) at faint levels. Conceivably the observations would be obtained in two consecutive nights.

4.4.4 Risks and Opportunities

A GRB can not be planned for SV. The imaging of a former GRB site is not a problem. Imaging of former sites of GRBs will also prepare the spectroscopic observations by FORS.

4.4.5 Publicity and Press Releases

The optical detection of a GRB is still an exciting event. Only a handful of these objects has been seen in the optical. Detecting a GRB at a fainter level than before is certainly possible.

These observations would provide some deep images of an extragalactic field, although much less deep than any 'deep field' observation.

4.5 SN 1987A

4.5.1 Rationale

The shock from the supernova is predicted to reach the inner ring only in the next decade. However, it is starting to ionize material left over by the fast, hot star wind. An HII region inside the ring, i.e. gas ionized by the 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 ionized 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. There have been reports from STIS that high-velocity Lyα from inside the ring has been detected.

The ring itself has started to brighten in a single spot. So far it is undecided whether this brightening is due to changing ionization or an early interaction of material which did not suffer any slowing by shocks.

4.5.2 Technical Issues

There are two bright stars very close to SN 1987A. It is very important to achieve low scattering profiles on the PSF. The micro-roughness of the mirror is the most significant contributor to the wings.

Images can be 'sharpened' by deconvolution techniques making use of the spatial information from HST images.

Narrow-band filters for [O III] and Hα are required for these observations.

4.5.3 Risks and Opportunities

The high spatial resolution is critical for these observations. The reconstruction with HST images will be important to find the faint surface brightness structures.

4.5.4 Publicity and Press Releases

Images of SN 1987A are well known from HST press releases. A suitably processed VLT image showing faint surface brightness features could rival the HST images in impact.

4.6 UV imaging of HST fields in globular clusters

4.6.1 Rationale

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 $\sim 10\,\mathrm{Gyr}$, it is still not at all clear how the stellar population in their cores would react to strong densities (up to $\sim 10^9\,\mathrm{M}_\odot\ \mathrm{pc}^{-3}$) 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 cataclismic 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 clusters cores conducted with the Faint Object Camera on board the 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 enormous 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 at best 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.

4.6.2 Technical Issues

Excellent seeing is required for this project to succeed. Targets will be selected from the pool of those already observed with the HST. Images will be analyzed with a restoration technique developed at the ECF which makes use of high resolution astrometric information to reach high quality photometry of stellar objects in ground-based crowded fields. The PSF possibly will have to be determined in outer regions of the clusters (separate exposure).

4.6.3 Scientific Testing

¿From these studies the detection limits can be characterised using the simplest PSF - that of an unresolved point source. This is an optimum way to accurately quantify what are the driving factors in getting the faintest images possible (e.g. flat fielding strategies, weather conditions, instrument and telescopes adjustments) in as many different filters as possible. This will be fundamentally important information for all future users of the VLT.

4.6.4 Risks and Opportunities

The reduced UV sentivity of the VLT-TC may limit the scope of this experiment. The seeing is absolutely critical and so is the image restoration analysis. This is a unique observation which is best matched by the VLT-TC UV capabilities which may have the highest throughput at these wavelengths of all foreseen VLT instruments.

4.6.5 Publicity and Press Releases

Image restoration techniques developed at the ECF will help produce rather spectacular, high-resolution images for press releases. The power of the VLT could thus be made evident to the large public as well. This program is a clear demonstration of the capabilities of the VLT as these observations could not be obtained at smaller telescopes even with long exposure times. These observations very nicely illustrate the complementarity of the VLT and HST.

4.7 Timing of Pulsars

4.7.1 Rationale

The first pulsar detected in $\gamma-$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 $\gamma-$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 $B \simeq 26.5$, but no pulses have been detected due to its faintness. Measuring the optical pulses would provide information on the energy processing in the neutron star atmosphere which has never been done before. Optical broad-band photometry indicates a non-thermal spectrum with a large depression in the B band (or conversely a large emission in V). Accurate broad-band photometry especially in UV bands is thus much needed.

The VLT-TC can achieve a S/N of 10 (corresponding to a photometric error of about 0.1 magnitudes) in about 900 seconds in B. For a similar accuracy, the integrations in V, R, and I are 400, 600, 300 seconds, respectively for a seeing of $0\farcs7$. For the U filter only a detection is targeted. The pulse measurement can be achieved by repeated integrations while moving the charge on the CCD. Since the pulse period is known very accurately (237.097 msec) we can clock the CCD at exactly this rate and move the charge back and forth.

4.7.2 Technical Issues

The CCD will be binned to a pixel scale of $0''.15$ pixel^{-1} (i.e. 3×3) for a seeing worse than $0''.5$ or $0''.1$ pixel^{-1} for seeing better than that. The image quality is not really critical, but good seeing ($< 1''.0$) will considerably improve the S/N.

4.7.3 Scientific Testing

The precise timing of this pulsar will allow accurate testing of the CCD controller as well as of the coordination of the telescope/instrument control software.

4.7.4 Risks and Opportunities

The availability of charge shifting on the VLT-TC CCD is not guaranteed. FIERA is not quite ready to do this. The observations depend on a smooth operation of the whole camera. The detection of optical signals from pulars will open up a new era for neutron star physics.

4.7.5 Publicity and Press Releases

Geminga has been described as the last supernova near the sun. Optical pulses have so far only been measured from the Crab and the Vela pulsar. The capabilities of the VLT and a new observing technique would be demonstrated.

5 Lower priority observations

5.1 Giant arcs in clusters

5.1.1 Rationale

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. The nature of the distant objects can be investigated through surface photometry of the arcs and arclets produced by the lens: for example, the blue color of most giant arcs immediately suggests the presence of young stars. 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. In fact, the origin and nature of these faint blue galaxies is still one of the most puzzling issues of today's Astrophysics. Even more interesting is the determination of photometric redshifts of the lensed objects, which would require a filter set like the one adopted for the Hubble Deep Field (see 4.2) and is made possible because gravitational lenses are achromatic. Broad band observations of distorted galaxies have been used to infer the redshift distribution to R=27 (Kneib et al. 1993) with a 4-m class telescope. Since the asymmetry is best observed at the faint, outer isophots the VLT can significantly increase the S/N.

5.1.2 Technical Issues

The large collecting power of the VLT is a prerequisite to accurately measure the magnitude of the objects in the arcs and arclets. The more precise their colors and luminosities can be determined, the better constrained would the determination of their redshift be, particularly if broad-band filters have to be used.

5.1.3 Scientific Testing

These observations would provide a way of testing the photometric performances of the VLT-TC setup as well as of the tracking stability of the telescope.

5.1.4 Risks and Opportunities

The surface brightness level required may be lower than anticipated and the SV observations can not reach the required faint magnitudes. Also the spatial resolution might not be sufficient to disentangle the distant objects. The VLT-TC will be the first instrument on the VLT with which this experiment can be tried.

5.1.5 Publicity and Press Releases

This program is well suited to demonstrate the capabilities of the VLT and would deliver rather spectacular pictures for press releases and publicity. Those images would provide a clear example of the concept of gravitational lensing.

5.2 QSO host and companion galaxies

5.2.1 Rationale

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 (Bahcall et al. 1997) 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 color 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 colors through broad band imaging can teach us about the influence of the central power house on the surrounding material.

Recently narrow-band imaging at the redshifted Lyα wavelength have discovered faint, extended material around QSOs. So far these detections have been made with spectrographs at Keck only. Good imaging of a few sources would contribute to the study of the environments of quasars. In a few cases a damped Lyα absorbers close the the QSO redshift can effectively block the Lyα emission from the quasar and act like a coronograph. In such cases the brightness difference is greatly diminished.

5.2.2 Technical Issues

The large brightness contrast between the bright nuclear region (a point source for all telescopes) and the galaxy requires a large photon collecting power and small pixel sizes so as not to saturate the point source (PSF), yet still reveal the comparatively faint surface brightness host. The VLT-TC is well suited for such a study. The light collecting power of the telescope, the large oversampling of the PSF, and the occulting focal plan mask will allow us to accurately subtract or suppress the QSO light and measure the faint underlying surface brightness structure.

5.2.3 Scientific Testing

These observations will also allow us to test the telescope and instrument performance under high dynamic range conditions and the stability of the PSF, as well as to characterize the microroughness of the VLT mirrors by inspecting scattered light in the wings of the PSF.

5.2.4 Risks and Opportunities

Companion objects to high-redshift quasars have been reported in almost all cases where such a detection was attempted. Yet there remains the possibility that no object is found. A small sample should be sufficient for a detection.

5.2.5 Publicity and Press Releases

This program is well suited to demonstrate the capabilities of the VLT and would deliver potentially exciting images of gas ejected by the QSO.

5.3 Proper motion projects: TNOs

5.3.1 Rationale

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 resp., 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 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 54 TNOs discovered, the only magnitude available is a crude estimate made from the discovery image, and only a few have color measurements. These measurements were obtained by a wide range of observers, using different set-up and calibration, and are affected by large errors. Similarly, only about a dozen of short period comets and a couple of the Centaurs have been measured. The theoretical models are now at a level of complexity that should not be increased without observational input. For instance, the SP Comets and TNOs are supposedly related bodies, but the information we have on their size distribution seems to be incompatible with these hypotheses.

As a by product, every image would be astrometrically measured in order to improve the orbits. The images would also be scanned for new objects. The very faint limiting magnitudes reached by the VLT ($R\sim28$ for stacked lightcurve images) and the baseline of the lightcurve observations would allow us to scan some unknown regions of the Kuiper belt (much smaller diameters and larger heliocentric distances than any of the current surveys), further constraining the distribution of these objects.

5.3.2 Technical Issues

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 minimize 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).

5.3.3 Scientific Testing

The large collecting power of the VLT and the high throughput of the VLT-TC are key issues in this project. The tracking accuracy of the telescope and differential tracking are important.

5.3.4 Risks and Opportunities

There is no shortage of objects. The analysis of the data is critical and has to be performed by experts. The SV team has to make sure that the community astronomers will make use of this data, as none of the SV team members is an expert in this research field. There is, however, sufficient expertise among the ESO staff to perform this analysis.

5.3.5 Publicity and Press Releases

True-color images of objects with different chemical properties would be rather dramatic. The outer solar system is still closer to home than much of the distant universe and appeals to the public. Deductions on the origins and evolution of the solar system are possible.

A SV Policy Statement

VLT Science Verification Policy

General Remarks

Performance verification of the scientific capabilities has been a regular feature of space missions and in this approach it is the goal of the VLT Science Verification (SV) to provide the community with fully understood and tested telescopes and instruments. Therefore, after the commissioning period a set of typical scientific observations should verify and demonstrate to the community the capabilities of the telescopes and of the instruments in the operational frame of the new VLT Observatory. During SV the correct interplay between the various hardware and software under the VLT operational paradigm will be checked with representative science observations. For community astronomers SV will deliver data allowing them to assess promptly the suitability of the VLT and its instruments for their scientific programs, thus submitting the VLT to a wider scrutiny.

The SV plans will be made public (through the Messenger and the ESO Web page), and the active involvement of the community will be sought. The observations and assessment of the data quality will be performed by the SV Team. All data from SV will enter the ESO public archive as soon as possible and no rights could be claimed on them. SV will be under the supervision of the VLT Programme Scientist.

In the following two distinct areas of SV, the telescope and the instruments, are considered.

Telescope Science Verification

Science verification of the VLT Unit Telescopes will be done by the SV Team, which involves astronomers from all ESO divisions dealing with the VLT development. A close integration with the Commissioning Team is taken for granted and necessary for essential feedback. The VLT Test Camera will be the instrument of telescope Commissioning as well as SV.

The SV of UT1 will include the first dark run after Commissioning of the telescope and is currently foreseen from August 18 to September 8, 1998. It will last for at least the full length of the dark period (approximately 2 weeks).

The selection of the SV observations is under the responsibility of the VLT Programme Scientist, and the SV plan will be transmitted to the OPC for information. Should plans for the Hubble Deep Field South be advanced enough the same field may be included in the SV plan.

Instrument Science Verification

A SV phase will also take place for each of the VLT instruments, and shall document their scientific performance, limits, and correct operational setup. For this purpose the SV Team will be joined by the instrument PI (or his/her representative) and by the ESO Instrument Responsible.

The instrument SV will last for about one week following the second commissioning phase (system optimization) of the instrument and will cover all instrument functions. The selection of the SV observations is under the joint responsibility of the VLT Programme Scientist and the instrument PI. The instrument SV plan will be transmitted to the OPC for information. No observations which have been previously approved by the OPC will be performed during SV, unless the proposers agree.

Science Verification Team

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