Field Stabilisation on the ESO VLT telescopes

Gianluca Chiozzi[*], Robert Karban, Krister Wirenstrand

European Southern Observatory, Munich, Germany

ABSTRACT

The Field Stabilisation functionality compensates for image motions, mainly due to wind gusts, with a frequency of up to 50 Hz. Position errors are detected with a CCD mounted in the guide probe, and the correction vectors are passed to the secondary mirror, which can perform tip/tilt corrections with a frequency up to 100 Hz. This functionality is in regular use on the first two VLT telescopes, Antu and Kueyen; on Antu in operational use since 1st of April 1999 and on Kueyen for commissioning tests. In fact, Field Stabilisation is ALWAYS used during observations. It is started as an integral part of the setting of the telescope. This paper describes the software and hardware that performs the Field Stabilisation functionality. The architecture of the system, both software and hardware, is presented, with a discussion about problems and special solutions. The actual status, including some results from the commissioning and operational phases of the two first telescopes, is described. Finally, we present a short discussion about possible future extensions and improvements.

Keywords: VLT, VLTI, Telescope Control Software, Field Stabilisation, Auto Guiding, Chopping.

1. INTRODUCTION

The VLT Auto Guiding software takes care of correcting the telescope position for errors of low frequency (< 1 Hz) during tracking. Corrections are done to the telescope position, i.e. to the altitude and azimuth axes. The Auto Guiding is NOT supposed to correct for variations in atmospheric or local seeing, except for slow variations, i.e. the part with frequencies < 1Hz. In order to support a bandwidth of 1Hz for corrections, the actual correction frequency must be of 5 to 10Hz.

The Field Stabilisation software takes care of correcting tracking errors with an increased bandwidth compared to Auto Guiding. In particular it is used to correct for wind buffeting errors. High frequency corrections, measured with the guide camera, are sent to the M2 tilt facility. The closed loop bandwidth required for wind buffeting corrections (based on the results of simulations) is assumed to be 2Hz. This implies a guider measurement frequency of around 20Hz[4]. Using a standard ESO Technical CCD acquisition software, the system is capable of working with frequencies up to about 50Hz.

Using more powerful HW platforms or different acquisition systems, the performance can be pushed to higher frequencies. Using a STRAP system [5](based on an Avalanche Photo Diode (APD) detector instead of a CCD), correction frequencies can be pushed to 100Hz, covering higher order corrections due to atmospheric tilt errors. A closed loop bandwidth of up to 10Hz would be required in the worst case, requiring a maximum sample rate of up to 100Hz[4].

The Field Stabilisation module is able also of supporting a Rapid Guiding mode, using error signals derived from a sensor in the isoplanatic patch and incorporated into the science instrument itself. This would be able to correct for atmospheric tilt effects as well as global tilt errors.

It was clear since mechanical design of the VLT that Field Stabilisation was necessary to get from the telescope the required tracking performance, since the structure was known to be not stiff enough to remove the effects of the wind on the focal plane[8]. Just during the first tests before first light, it appeared that the urgency was even higher than expected: altitude blind tracking performance was clearly out of specification[2]. In early 1999 this limitation of UT1 was identified to be due to a noisy tacho signal fed into the tracking velocity controller and solved.

In order to compensate for this problem, Field Stabilisation was implemented ahead of time for First Light (see [3] for an entertaining narration of the commissioning of the VLT UTs). From then on, basic Auto Guiding has been never used in practice, a part from some very specific observing conditions, and Field Stabilisation performances have been constantly improved first during commissioning of UT1 and then during commissioning of UT2. The possibility of having 4 identical

---

[*] Correspondence: Email: gchiozzi@eso.org; WWW: http://www.eso.org/~gchiozzi; Telephone: +49-89-32006 543

Unit Telescopes to commission (and 3 smaller Auxiliary Telescopes[7]) provides a unique opportunity for tuning and improving the control system[2].

2. FIELD STABILISATION SYSTEM ARCHITECTURE

The VLT Field Stabilisation System is based on the interaction between three main subsystems of the telescope:

- Main tracking axes control system (altitude and azimuth)
- M2 fast tip/tilt control system
- Guide and Acquisition System

The following block diagram shows a simplified model of the actual servo system for Field Stabilisation:

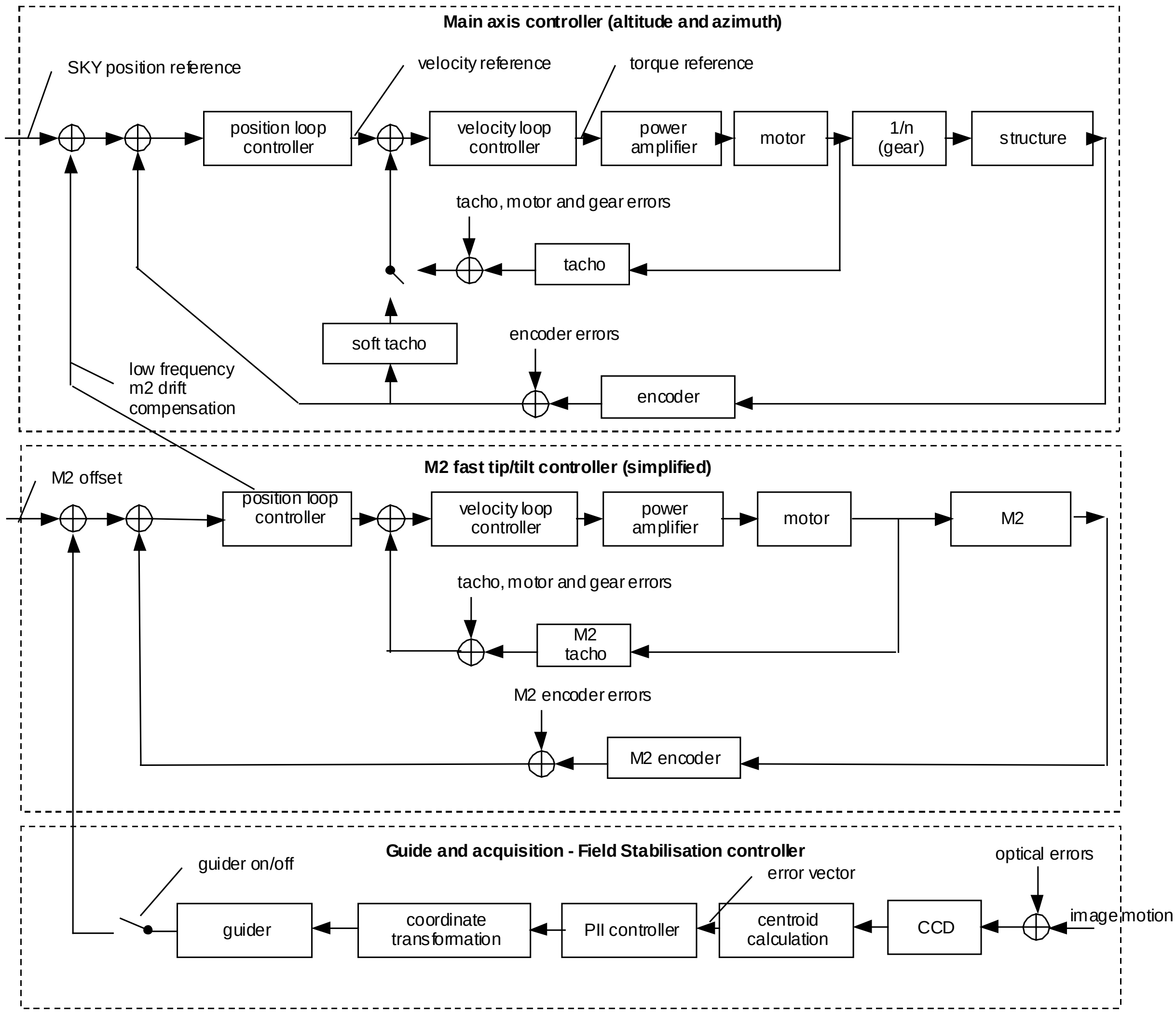


Figure 1 - Block Diagram for the VLT Field Stabilisation servo system

2.1 Guide and Acquisition System

The Field Stabilisation controller is part of the Guide and Acquisition system, so called because the Technical CCD mounted on the guide probe is also used for field acquisition.

During guiding, each frame acquired by the CCD is processed in order to determine the position of the centroid of the guide star.

The CCD image processing, described in details in [10], includes Bias subtraction and Flat Field correction and implements an automatic evaluation of image background and threshold for fast centroid calculation as shown in Figure 2.

The sky background level is estimated as the average of the 3 less illuminated corners of the window and the threshold is set to 3 times the sky RMS. This ensures a proper discrimination of the valid pixels so as not to bias the centroid position.

In addition, the image statistics (FWHM, SNR...) are used in a configurable multi-criteria validation procedure yielding a confidence measure of the centroid. This is necessary since the centroid intensity alone is not a reliable indicator of the detection of an object in the image [10]; especially it is important that no correction is sent to M2 when the guide star can not be located unambiguously in the image.

The difference between the pixel reference position on the CCD and the measured actual position is the error vector that has to be corrected for.

A standard PII (Proportional-Integral-Integral) regulator with integrator limit is then applied to the error vectors.

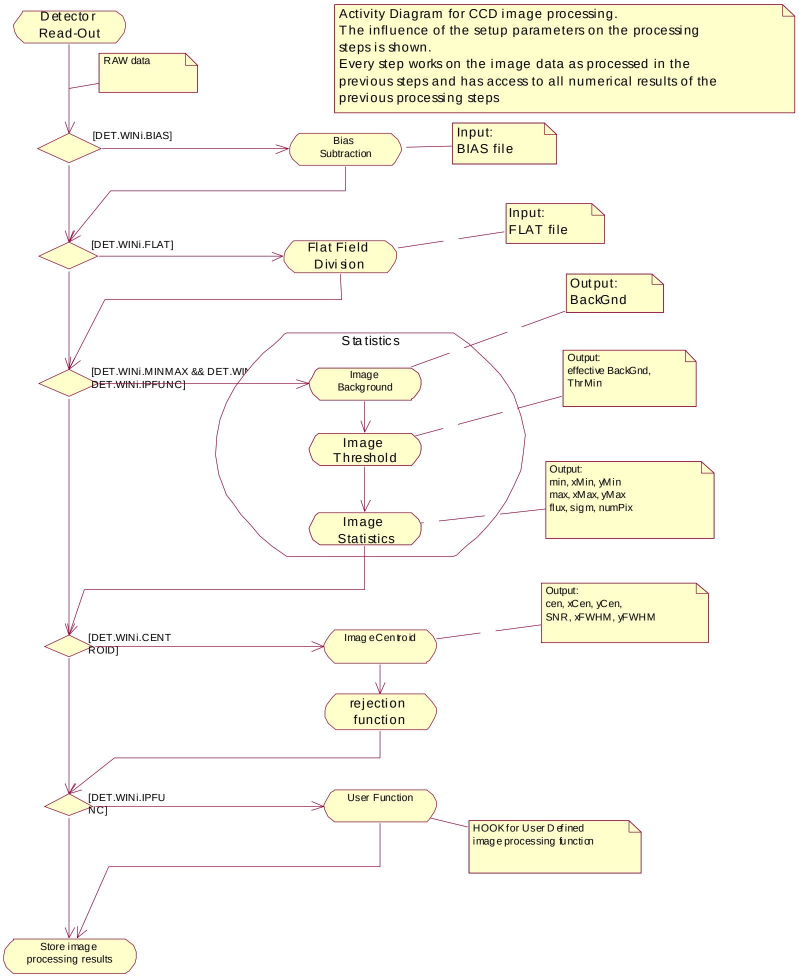

Activity Diagram for CCD image processing.
The influence of the setup parameters on the processing steps is shown.
Every step works on the image data as processed in the previous steps and has access to all numerical results of the previous processing steps

Figure 2 - Activity Diagram for CCD Image Processing

In practice, we have seen that the dynamic behaviour of M2 fast tip/tilt system is so fast compared with the Field Stabilisation control loop at the frequencies we can achieve now (about 50Hz), that it can be considered a perfect system. We can then apply a direct transfer function with (Kp=1, Ki=0, Kii=0). This is not the case for basic Auto Guiding, where a proper tuning of the PII parameters is essential to achieve required performances.

The obtained corrections are then converted from CDD pixel co-ordinates into sky co-ordinates (right ascension, declination) to be sent to the M2 fast tip/tilt control system (or directly to the main axes during basic auto guiding).

Before actually sending corrections, the guider system checks if they fulfil predefined acceptance criteria (to avoid, for example, sending corrections too small or too big). It also calculates statistics useful in assessing the performances of the guiding system.

2.2 M2 fast tip/tilt control system

The M2 fast tip/tilt subsystem accepts field stabilisation corrections at high frequency directly in sky co-ordinates (right ascension, declination) and is able to superimpose the corrections to alignment and focusing offsets and to the chopping mode.

The actual servo system [12] is more complicated than shown in the block diagram and provides excellent performance that will be fully used only by much faster error correction systems working in Rapid Guiding mode (see Section 6).

To avoid driving M2 into limit, due to slow tracking drifts, the M2 position loop controller takes care of off-loading at low frequency to the main axis. At a typical frequency of 1Hz, it sends to the main axes Auto Guiding corrections (see Section 2.3) corresponding in sky co-ordinates to its own current offset from center position. While the telescope axes slowly, compared to the Field Stabilisation time scale, drift to their new reference position, the feedback from the CCD drags seamlessly M2 back toward center position.

2.3 Main tracking axes control system (altitude and azimuth)

The control system for the altitude and azimuth axes receives from M2 (or, during basic Auto Guiding, directly from the guiding software) Auto Guiding corrections in sky co-ordinates. The correction is converted in (alt,az) co-ordinates and fed to the axis controller.

During the commissioning phase of UT1 and UT2, the VLT main axis drive system has been extensively modified to solve initial problems and to improve its performance. Now it fully meets its specifications[2][9]. Figure 1 sketches the current architecture of the servo system.

Inside the tracking pointing machine, Auto Guiding corrections are considered pure pointing corrections: the telescope altitude and azimuth are moved to the new reference position, but the sky co-ordinates of the target are unchanged based on the assumption "*we were looking in the wrong place*".

3. FIELD STABILISATION SOFTWARE ARCHITECTURE

The performance of Field Stabilisation is highly affected both by frequency and stability of the control loop.

Clearly, higher loop frequency allows correcting higher order errors, but this is not the only parameter.

Every processing step from image acquisition up to the final action on the M2 actuators introduces a delay (known as death time in control theory) that negatively affects the performance of the control system. More over, it is extremely important that sampling rate is constant in order to avoid time jitter that would as well cause performance degradation.

As a consequence, the implementation has to carefully take into account performance and real-time requirements. For this reason, if on one side we have followed VLT conventions and design rules we have also accepted exceptions to the rule when a clear performance gain was at hand.

Like most VLT subsystem, also Field Stabilisation is split into two components:

- A co-ordination part running on the TCS workstation takes care of all configuration and administration
- A control part running on a dedicated Local Control Unit (LCU) takes care of all real-time control and of interfacing with the hardware. LCUs are VME based systems running the VxWorks real-time operating system.

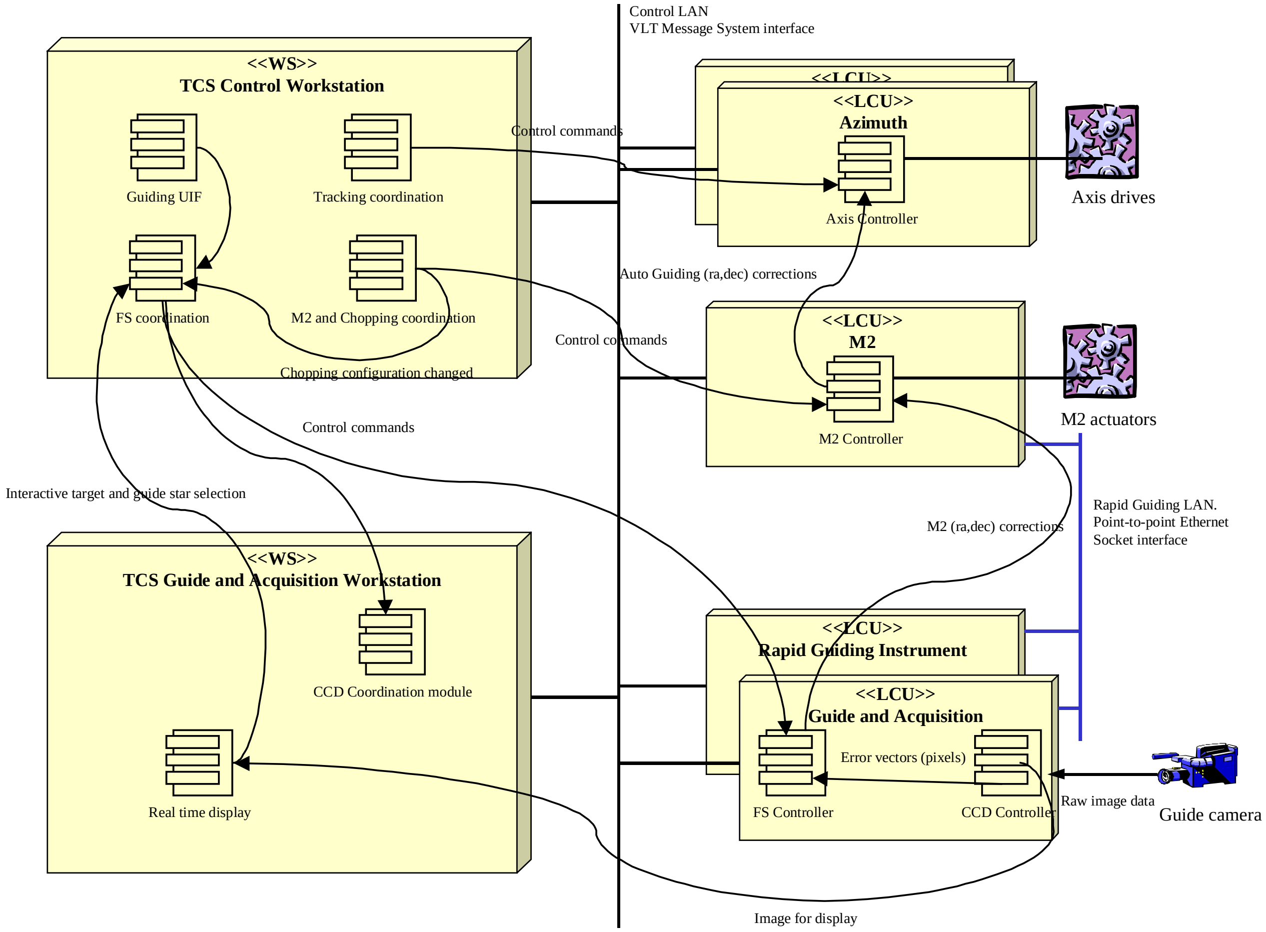


Figure 3 - Field Stabilisation deployment diagram

Normally, no direct communication between LCUs is allowed, but in this case performance and real-time requirements justify the exceptions:

- Both Field Stabilisation and M2 control software, running on the respective LCUs, are allowed to send directly Auto Guiding corrections to the tracking software running on the main axes LCUs. In this way we can easily reach 10Hz sustained correction rate to the main axis, without any need of special network configuration on a normal 10Mbits Ethernet. Corrections to the main axes do not have any other special requirement.
- The Field Stabilisation software is allowed to send directly position corrections to the M2 LCU. In order to warranty real-time behaviour, the Guide and Acquisition LCU and the M2 LCU are directly connected by a dedicated point-to-point Ethernet. The dedicated connection allows to have a deterministic behaviour of the network so that correction travel time and jitter are kept to a minimum allowing a stable control loop at 100Hz, as required for Rapid Guiding (see section 6).

Absolute time is distributed to all LCUs by a Time Bus [11] and a Time Board is used to generate high precision interrupts that are used to trigger all control loops and the exact start and duration of CCD exposures.

One of the more important characteristics of the VLT control system is the fact that every LCU performs its duties independently from the others without any direct synchronisation, but based only on the absolute time provided by the time bus. For this reason, all co-ordinates exchanged are in sky (right ascension, declination) reference system and are converted to (alt, az) or to whatever local co-ordinate system needed inside the LCU itself.

The Guide and Acquisition LCU is responsible for the control of the Technical CCD hardware. All image-processing functions as well as the actual Field Stabilisation control loop are deployed on this LCU.

Using this strategy and running the guide and acquisition software on a Motorola MVE 2604 motherboard with Power PC 604e 200 MHz CPU, we can achieve the following performance on an example with a 20x20 pixels window (0.2"/pixel on sky) and 10ms integration time:

- Wipe time = 1.9ms (constant; whole chip always wiped)
- Integration time = 10ms (dependent on guide star magnitude and on seeing)
- Readout time = 14.3ms (dependent on window size)
- Centroiding time = 0.3ms (dependent on window size)
- Co-ordinate conversion time = << 0.1ms
- Message propagation time to M2= ~1ms (constant on dedicated point-to-point Ethernet)
- M2 "move time" = 2.5ms (maximum settling time)

Actually the maximum loop frequency and the delay depend strongly on the window size and on the integration time, as shown in Table 1.

Table 1 - Maximum loop frequency in Hz as function of window size and integration time

Integration time **Win size**	**3ms**	**10ms**	**20ms**	**50ms**	**80ms**	**100ms**
15x15	65.5	45.1	31.4	16.0	10.2	8.9
20x20	55.6	40.1	28.6	15.3	10.5	8.7
30x30	42.2	32.7	24.6	14.1	9.9	8.3
40x40	33.9	27.5	21.6	13.1	9.4	7.9

It is clear from this table that the objective of the telescope operators is to have the smaller window and the shortest integration time, but these parameters depend on:

- the magnitude of the guide start: the fainter the guide star, the longer the integration time
- the seeing: the higher the seeing, the longer the integration time
- the wind: the stronger the wind, the bigger the window, to avoid loosing the guide star on strong wind gusts

Unfortunately, bad observing conditions limit the maximum loop frequency and the Field Stabilisation performance, where they would be more needed.

Currently, the typical window size is 20x20 and the most commonly used integration time is 10ms with a typical 12th magnitude guide star. Guide stars are selected in the 11th to 14th magnitude range, taking into account that the photons are split with a 80/20 ratio between the guider CCD detector and Active Optics detector with a beam splitter.

4. FIELD STABILISATION OPERATION

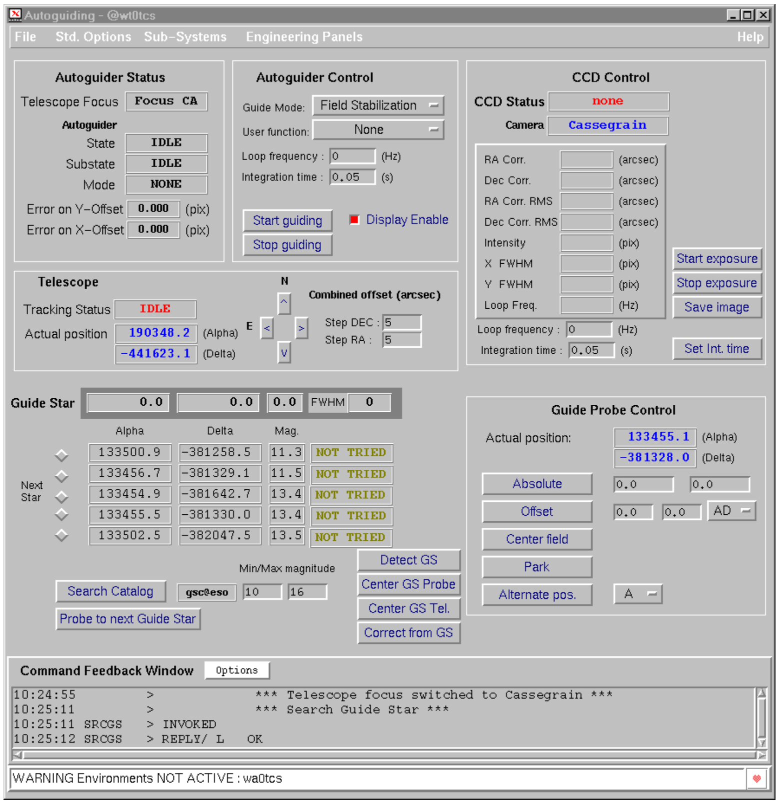
From the operational point of view, the Auto Guiding and Field Stabilisation software has been designed for easy operation and flexibility.

On one extreme, it can be operated in full automatic mode. Whenever a new observation template is executed and the telescope points to a new target, the system can be instructed to automatically:

- Look in guide star catalogues for a suitable candidate
- Position the guide probe to the selected guide star
- Acquire a first set of error vectors and correct telescope position to center the guide star on the detector (actually correcting for telescope pointing errors).
- Closing the Auto Guiding or Field Stabilisation control loops

This is now the normal operating mode.

On the other extreme, it can be operated in fully manual mode from a control panel (see Figure 4):



Telescope Focus: Focus CA
Autoguider State: IDLE
Substate: IDLE
Mode: NONE
Error on Y-Offset: 0.000 (pix)
Error on X-Offset: 0.000 (pix)

Guide Mode: Field Stabilization
User function: None
Loop frequency: 0 (Hz)
Integration time: 0.05 (s)

CCD Status: none
Camera: Cassegrain
RA Corr. (arcsec)
Dec Corr. (arcsec)
RA Corr. RMS (arcsec)
Dec Corr. RMS (arcsec)
Intensity (pix)
X FWHM (pix)
Y FWHM (pix)
Loop Freq. (Hz)
Loop frequency: 0 (Hz)
Integration time: 0.05 (s)

Tracking Status: IDLE
Actual position: 190348.2 (Alpha) -441623.1 (Delta)
Step DEC: 5
Step RA: 5

Guide Star: 0.0 0.0 0.0 FWHM 0

Alpha	Delta	Mag.	
133500.9	-381258.5	11.3	NOT TRIED
133456.7	-381329.1	11.5	NOT TRIED
133454.9	-381642.7	13.4	NOT TRIED
133455.5	-381330.0	13.4	NOT TRIED
133502.5	-382047.5	13.5	NOT TRIED

Min/Max magnitude: gsc@eso 10 16

Actual position: 133455.1 (Alpha) -381328.0 (Delta)
Absolute: 0.0 0.0
Offset: 0.0 0.0 AD
Alternate pos.: A

```
10:24:55       >         *** Telescope focus switched to Cassegrain ***
10:25:11       >         *** Search Guide Star ***
10:25:11 SRCGS > INVOKED
10:25:12 SRCGS > REPLY/ L   OK
```

WARNING Environments NOT ACTIVE : wa0tcs

Figure 4 - VLT Guiding control user interface

- Guide stars can be selected by point-and-click from the field acquisition display or from a catalogue
- Configuration parameters like integration time and loop frequency or PII gains can be set interactively
- Guide probe and telescope position can be manually corrected in a variety of modes
- Statistics are displayed to allow the operator to assess the performances of the guiding system and tune it.

The integration time can be modified interactively without interrupting guiding, but no adaptive determination of optimal integration time has been implemented.

5. SYNCHRONISATION WITH CHOPPING

The requirements for the VLT operation specify that it must be possible to perform Auto Guiding or Field Stabilisation while Chopping. This mode has been implemented and first tested on UT1 in October 1998.

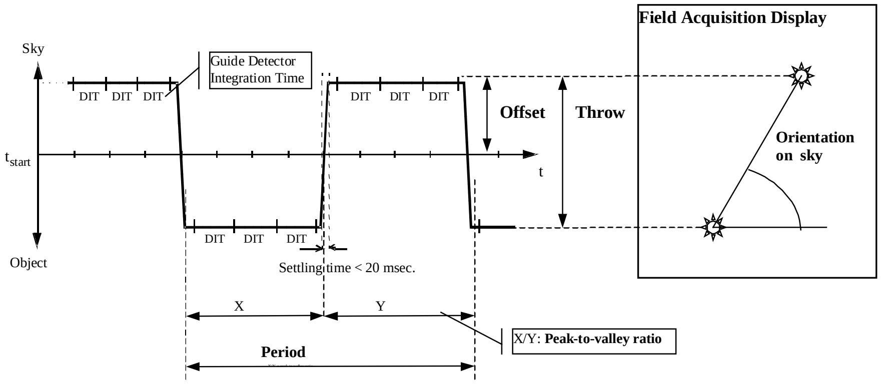


Figure 5 - Chopping configuration parameters

In Chopping mode, the M2 secondary mirror switches with a given frequency between two positions (called Object and Sky positions) that can be set to any orientation on the sky. The user can define (see Figure 5):

- Period of chopping cycle
- Chop throw
- Orientation on sky
- Offset in direction of chop
- Peak-to-valley ratio

As a consequence, the guiding system must be aware of the chopping configuration and the guider Technical CCD readout must be synchronised with chopping cycles. It is clear, however, that the dynamic response of M2 limits the capability of this mode of operation.

The VLT Technical CCD sub-system is capable of handling two simultaneous readout windows, so that image acquisition for Auto Guiding or Field Stabilisation can take place in both chopping positions, if for both positions the guide star fells in the field of view of the guide camera. This limits the maximum chopping stroke to about 30" on the sky, with Object position in the center of the CCD.

In this case, the Technical CCD software is configured to integrate over two readout windows, one per each chopping position. The guiding software uses at each iteration the centroiding data calculated for the box where the guide star was positioned during that exposure and discards the other one.

If the chopping stroke is too big and one box is outside the field of view, only the visible box is used and no corrections are sent when M2 is in the alternate chopping position.

For the VLT, active optics must be always active. As a consequence, one of the two chopping positions must be close to the reference pixel in the center of the guide camera, to allow active optics image analysis. For this reason currently the chopping offset must be 1/2 of the chopping stroke, so that the Object position is always in the middle of the guide probe, where image analysis for Active Optics takes place. More complex strategies, involving offsetting the guide probe position to allow any chopping offset, are foreseen but have not been implemented yet.

All synchronisation between chopping and guiding software is done based on absolute time using the Time Reference System and no direct handshake between M2 chopping software and guiding software takes place, following the general VLT software rule of avoiding real-time interactions over network whenever possible. If chopping configuration is changed, the guiding software is notified of the new parameters and of the requested chopping start time via an asynchronous event:

- If guiding is not active, the new configuration parameters are processed and the setup configuration prepared to be used at the next STARTAG (start-of-guiding command).
- If guiding is already active and the new parameters do not require changing TCCD configuration (for example only chopping frequency is changed and no stroke or chopping angle are changed), they become active immediately.
- If guiding is active and the new parameters require changing TCCD configuration, guiding is stopped, reconfigured and resumed.

Chopping is always started/stopped referring to an absolute time in the future. The guiding software receives this starting/stopping time and configures itself to handle error vectors accordingly.

Depending on the ratio between chopping frequency and guiding frequency, the procedure to synchronise the two functions must be different.

5.1 Guiding Frequency much higher than Chopping frequency

As we have already discussed, the operational objective of VLT is to have Field Stabilisation always active at the highest possible frequency.

The typical operational mode for concurrent Field Stabilisation and Chopping corresponds then to a Field Stabilisation frequency much higher than Chopping frequency. The original requirement for VLT[4] explicitly said that simultaneous Chopping and Field Stabilisation should have been allowed with Chopping frequency up to 0.25 Hz, but during UT1 commissioning this restriction has been removed, allowing the operator to freely decide the upper limit for the Chopping frequency. The requirement is just to allow for a sufficient number of guiding exposures in each chopping position to have a stable control loop (typically at least a minimum ratio of 10 between the two frequencies is necessary, leading to a maximum Chopping frequency of 5Hz when Field Stabilising at 50Hz).

In this case the Field Stabilisation software receives the chopping configuration parameters and makes sure that any frame acquired while M2 is not settled in one of the two positions is ignored and does not generate any correction. As well, if the second “sky” position is outside the guide camera field of view, all exposures taken while the M2 is in “sky” position are ignored.

5.2 High Chopping frequency

The VLT must support [4] Chopping frequency up to 10 Hz.

In this case, it is not possible to use Field Stabilisation and only Auto Guiding can be used, accepting degradation in tracking performances.

Auto Guiding is in this case much slower than Chopping. During one Auto Guiding iteration, the guide star will come and go many times from the guiding box corresponding to Object position, leading typically to an effective integration time of 1/2 the one defined.

No special treatment is then necessary, except for a requirement to the operator of setting accordingly the integration time.

6. RAPID GUIDING

The VLT Control Software foresees the possibility for an instrument to take over control on the guiding system. Some instruments (for example spectrometers) have special requirements for guiding that can be satisfied only evaluating guiding corrections directly on the isoplanatic patch. Other instruments can provide guide detectors much faster and with higher sensitivity than the Technical CCD installed on the guide probe, allowing to exploit the full dynamic range of the M2 control system.

We call this operational mode *Rapid Guiding,* since correction frequency goes in the 100Hz region and to distinguish it from Field Stabilisation.

Hand-over protocol and support libraries have been developed for this purpose. Assuming that the instrument is capable of providing corrections at the required frequency, the bottleneck is the communication protocol between the instrument and the M2 tip/tilt facility. For this reason a light socket-to-socket connection is used, instead of the standard VLT Message System[6].

Internally, the Auto Guiding module behaves like in normal Field Stabilisation mode, but corrections are disabled, in order to maintain the probe in the correct position for Active Optics and to keep under control the performance of Rapid Guiding.

7. COMMISSIONING RESULTS

It was clear from the very beginning that wind-shake would be one of the worst causes of image degradation for the VLT telescopes, in particular in times of good seeing. This problem turned out to be bigger than expected though, which was clearly demonstrated by the first tracking tests in high wind (> 10 m/s). The relatively slow autoguiding, which corrects errors up to approximately 1 Hz, is not appropriate for this purpose. The conclusion was that Field Stabilisation was needed

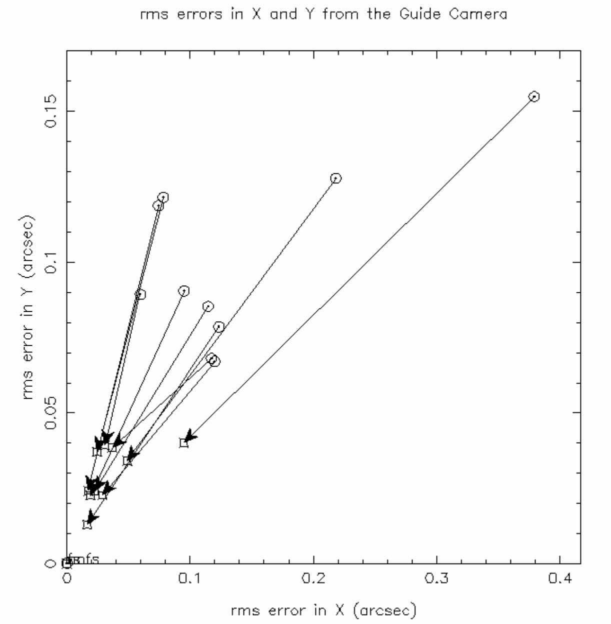


Figure 6 - Error vector rms, with and without FS. Wind speed ~5m/s

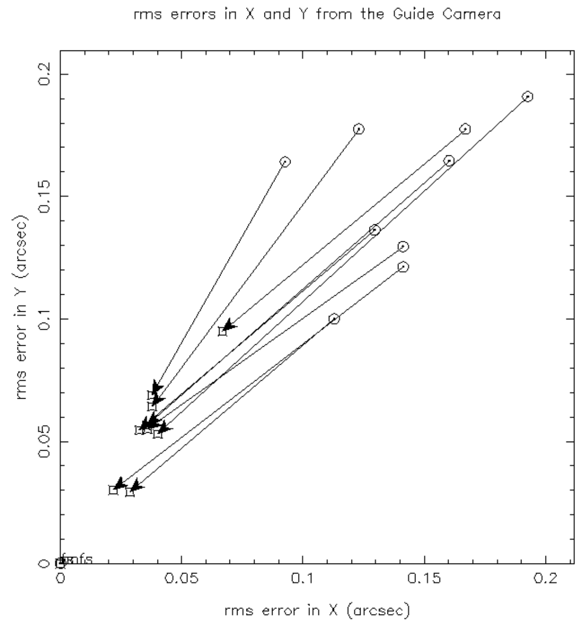


Figure 7 - Error vectors rms, with and without FS. Wind speed ~9m/s

in almost all cases, and it was decided at an early stage to routinely start Field Stabilisation as part of the regular setting of the telescope. The complete procedure involved in starting Field Stabilisation, i.e.:

- find guide star
- set the probe to the guide star
- center the star on the reference spot-start CCD exposures
- start correcting

was initially manually executed, but it was stepwise automated and it is now completely automatic.

The wind-shake was a problem only for the altitude axis (the azimuth was very little influenced), but measurements suggested that the effects were "too big", i.e. there was a discrepancy compared to mechanical analysis, and compared to other measurements. Eventually the reason was found: one of the tacho cables was picking up noise, and this noisy signal was fed into the velocity controller of the altitude axis. The problem was fixed, and then the altitude axis was "only" as sensitive as expected. Which still means that the Field Stabilisation is needed, and does a good job.

The effect of Field Stabilisation has been systematically measured for different operating conditions, like co-ordinates, wind speed, wind direction and seeing. For each measurement point two measurements are done: one with and one without using Field stabilisation. (Obviously, the two measurements should be done as close in time as possible, to keep the same operating conditions.) The measured variable is the error vector as received from the guiding CCD. In parallel, images are taken with a test camera. The rms values for the error vectors are calculated (using a 3rd order fit for the non-field Stabilisation data to delete any tracking drift), and the difference vector "with-without" is plotted.

Figure 6, Figure 7 and Figure 8 show such measurements for the UT2 for different wind speeds, and Figure 9 is a concatenation of all measurements. The data for Figure 6 were taken before the correction of the tacho signal, the others were taken after; even though Figure 6 represent data for the lowest wind speed of the three, the biggest errors without Field Stabilisation are found there.

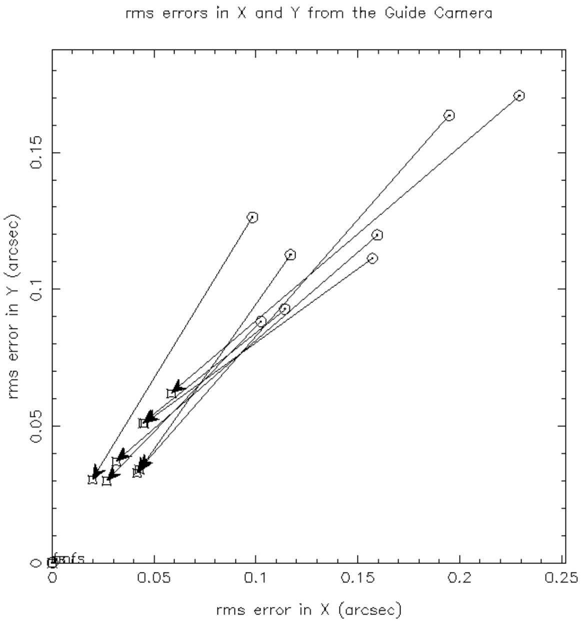


Figure 8 - Error vector rms, with and without FS. Wind speed ~15m/s

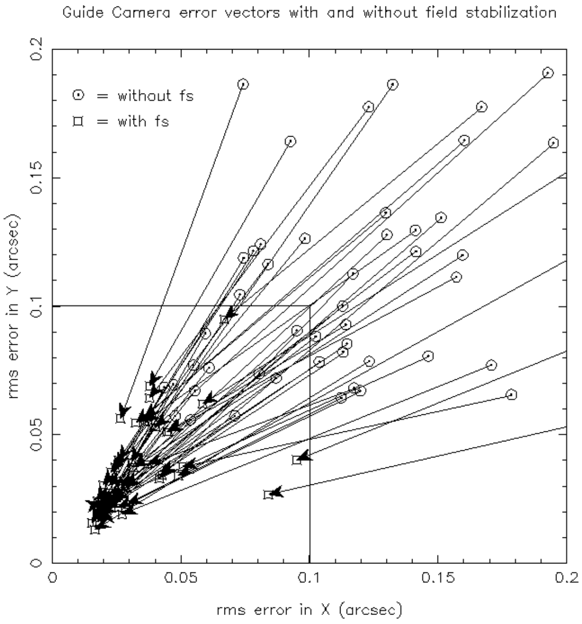


Figure 9 - Error vector rms, with and without FS. various wind conditions superimposed.

8. FUTURE DEVELOPMENTS

The VLTI Auxiliary Telescopes[7] will be equipped with a new STRAP[5] guide detector, based on a Avalanche Photo Diode (APD) head, and thus the Field Stabilisation for these telescopes will be implemented for this detector. The corrections will be done to a small and fast mirror (M6). Since the APD allows much shorter integration times than the CCD used so far, the complete system is expected to be much faster than the present one, so that it will be possible to correct high frequency atmospheric disturbances. This complete system is, however, still in an experimental phase, and the performance evaluation is still to be done.

It is also foreseen at a later stage the installation of STRAP units on the VLT Unit Telescopes to drive the M2, replacing the current Field Stabilisation based on CCD image acquisition.

9. CONCLUSIONS

The Field Stabilisation was originally planned for use in special observing conditions only, but has become an essential part of the telescope control system, and is now routinely used. The full functionality is implemented, also the cases of Field Stabilisation used in parallel with chopping and Rapid Guiding by an instrument. Though basically working, the performance for these two last cases is not yet systematically verified.

The standard mode however, is well tested. It is performing well, and helps the telescope stay within specified tracking and guiding errors, also in bad operating conditions, i.e. with high wind speed.

10. ACKNOWLEDGEMENTS

The authors wish to thank all colleagues in the Technical Division of ESO, and any other ESO staff, who have contributed to the concepts, ideas and software reported in this paper. A particular thanks goes to Than Phan Duc who has given an essential contribution to this Auto Guiding and Field Stabilisation software and to Philippe Duhoux who is the main responsible for the CCD and image processing software.

The Telescope Control System uses software packages for co-ordinate calculations, and for pointing analysis, written by P.T.Wallace, Rutherford Appleton Lab. These packages have been successfully used on the VLT and many other ESO telescopes.

11. REFERENCES

1. G.Chiozzi K.Wirenstrand M.Ravensbergen B.Gilli, "Integration Tests of the VLT Telescope Control System", Proc. SPIE 3112, 1997
2. A.Wallander J.Spyromilio K.Wirenstrand, "Commissioning VLT unit telescopes: methods and results", Proc. SPIE 4004, paper 35, Garching, 2000
3. J.Spyromilio, A.Wallander, M.Tarenghi, "Commissioning of the Unit Telescopes of the VLT", The ESO Messenger, No. 98, pp.21-24, 1999
4. M.Cullum, "Overview of Chopping & Field Stabilisation Modes, VLT-TEL-93/0244, Internal Memorandum, Garching ESO, 1993.
5. D.Bonaccini, J.Farinato, M.Comin, "ESO-STRAP units", *Adaptive Optical System Technology*, Proc. SPIE 4007, paper 45, Garching, 2000
6. B.Gilli, "Workstation environment for the VLT", Proc. SPIE 2199, pp.1026-1033, 1994
7. B. Koehler, C. Flebus, "VLTI Auxiliary Telescopes", Interferometry in Optical Astronomy, Proc. SPIE 4006, paper 03, Garching 2000.
8. M.J.Cullum, D.Enard, M.Ravensbergen, "Control of image position errors with the VLT", Proc. SPIE 2199, pp. 959-968, 1994
9. T.Erm, P.Gutierrez, " Integration and tuning of the VLT drive system", Proc. SPIE 4004, paper 20,Garching, 2000
10. P.Duhoux, "Image Processing Algorithms for TCCD Systems", VLT-TRE-ESO-17240-1689, Technical Report, Garching, ESO, 1998
11. F. Biancat Marchet, B. Gustafsson, P. Gutierrez, " The VLT Time Reference System: A Microsecond-Accurate Time/Synchronisation Bus for Distributed Control Systems", ", *Proc. ICALEPCS '99*, Trieste, Italy, Oct. 1999
12. "VLT M2 Chopper Controller Description ", VLT-TRE-DOR-11200-0064, Technical Report, Garching, ESO, 1997