Integration tests of the VLT Telescope Control System

Gianluca Chiozzi, Krister Wirenstrand,
Martin Ravensbergen, Bruno Gilli[1]

European Southern Observatory (ESO)
K.Schwarzschildstr.2, 85748 Garching, Germany

ABSTRACT

The installation of the complete VLT telescope control system on the observatory is a complex task. It is important that the various components of the system have been carefully tested and integrated before.

This paper presents the ESO strategy to pre-installation testing. In particular, results and experiences from pre-erection tests of the telescope structure are presented. In these tests, the complete telescope structure, including both axes with encoders and drives, has been built up at the premises of the European manufacturer (in Milan, Italy). These tests provide valuable input for the erection on Paranal.

To this system, ESO added control electronics and software, which was tested with the telescope. The complete positioning of both main axes is under test, including slewing and tracking performance tests, as far as this is possible without using the sky. The VLT control software and most parts of the VLT control electronics have also been tested on the NTT on La Silla. Since the NTT upgrade software is practically a subset of the VLT software, the NTT tests have provided invaluable feedback for the VLT. The NTT tests are described in a separate paper presented at this conference[7].

The paper also briefly discusses subsystem tests, and presents results from some of the subsystem tests performed in Europe.

Keywords: control system, real time control, testing, telescope, integration.

1. INTRODUCTION

The Very Large Telescope (VLT) of ESO, under construction at Paranal, in the Atacama desert in Chile, consists of an array of four alt/az style telescopes of 8m diameter.The mechanical structure of the first unit telescope is now under erection and first light is foreseen for early '98.

The design of the VLT unit telescope is based on an alt-az mount 22m long, 20m high and 10m wide, for a movable mass of 430t, including all the optical components and instrumentation. The system adopts drives and encoders directly mounted on the rotating alt and az axes, as well as directly mounted tachometers to generate the motor speed signal[2]. The direct encoder's technology if based on the Laser Doppler Displacement Measurement (LDDM) technique[1].

Because of the complexity of the system and of the very tight schedule between the erection in Paranal and the first light, the preliminary test and integration of the various components of the system has been considered very important and a big effort has been spent in planning the integration strategy, that is based on tests at ESO premises in Garching, on the NTT telescope in La Silla and on a first complete telescope structure at the premises of the European manufacturer (in Milan, Italy).

The paper presents first a brief summary of the main goals and performance requirements for the system in order to provide the basic background that justifies the solutions selected for the control system.

Then the control system structure itself is described in order to identify what components need to be tested and characterized on the real telescope and what components can be effectively tested and tuned on the NTT telescope, in Garching or on the structure built in Milan.

Each of the following sections analyses in details the tests that have been or are being performed or that will take place in the following months with these different test setups. The results that are available up to now about measured performances, in particular for what concern Milan tests.

Finally, conclusions are presented.

1.For further information - Email: gchiozzi@eso.org, kwirenst@eso.org, mravensb@eso.org, bgilli@eso.org

2. THE TELESCOPE CONTROL SYSTEM

The VLT Telescope Control System (TCS) is composed of a number of subsystems and the coordinating software, implementing a distributed system along the lines of the “standard architecture” commonly used for large experimental control systems[4].

A subsystem is a more or less independent electro-mechanical unit, with its own mechanics, optics, control electronics and control software.

Subsystem control software is implemented in Local Control Units (LCUs), with normally one LCU per subsystem. LCUs, based on VME systems running the VxWorks Real Time Operating System, are responsible for all tasks with real time requirements and in particular for digital and analog I/O, motor and encoder control, implementation of control loops.

On the other hand, coordination between the subsystems is provided by the Workstation Coordination Software, running on Unix workstation without hard real time requirements.

The synchronization between the subsystems is warranted by a dedicated time-bus that distributes accurate time, but the direct communication between subsystems is limited only to very special cases. The subsystems themselves are as much independent as possible in order to reduce the need of any direct synchronization to a minimum, that would imply exchange of messages through the Local Area Network (LAN).

This independence is one of the main characteristics of the control system architecture. For example, the altitude, azimuth and rotator subsystems track the target object in a completely independent way: they receive from the coordinating tracking software a complete set of target coordinates in sky reference system (alpha, delta, epoch...) and perform the full astronomical and pointing coordinate conversion up to their own specific encoder reference value (Fig. 1)[6].

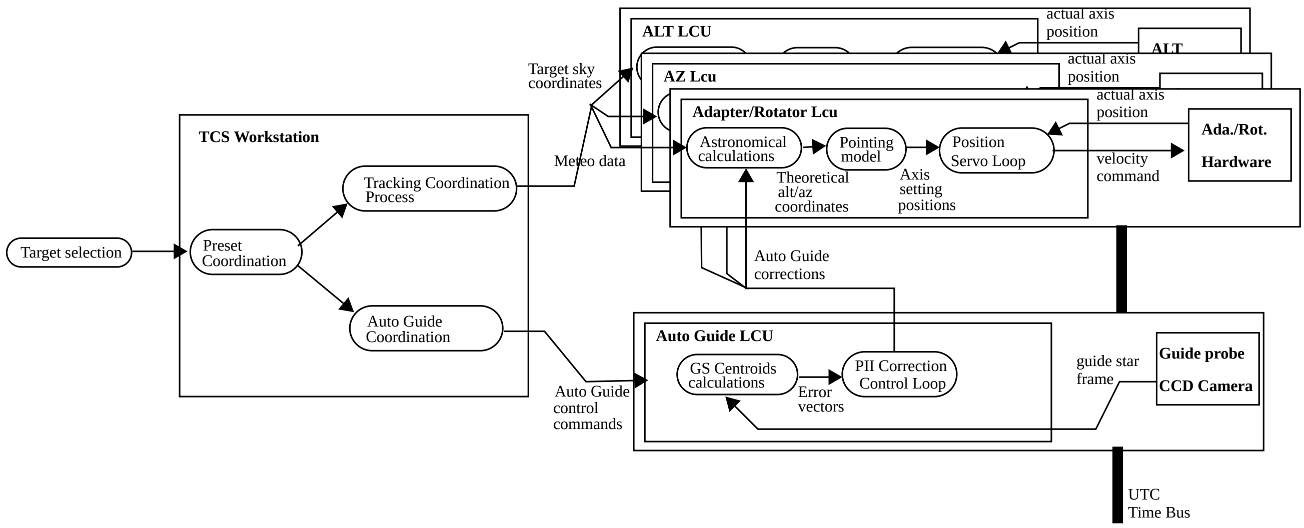

Fig.1:VLT TCS Tracking and Auto Guiding

The design of the VLT Telescope Control Software makes extensive usage of Object Oriented design methodologies[5]. The Workstation Coordination Software is written mainly in C++ and is based on a class library that provides an event-driven application architecture, very well suited for high level coordination systems. Lower level subsystem software is written in C. A lot of attention has been put on reusability, to allow the VLT Telescope Control Software to be used also for the NTT, the VLT Astronomical Site Monitor, the VLT Auxiliary Telescopes, the ESO 3.6 Telescope in LaSilla and possibly other ESO telescopes.

3. TESTING AND INTEGRATION STRATEGY

The testing and integration of the Telescope Control System before the final tests on Paranal is composed of the following steps:

- Development -> modular tests/regression tests

- NTT -> field tests for software and procedures
- VLT Model -> regression tests / hardware
- Milan -> field tests, control loop tuning, electronics, characterization of performances

Compared to original ideas, the strategy of testing has shifted:

- more effort was spent on testing and bug fixing at the NTT
- the VLT Control Model (See section 5) will be used in a more realistic and complete way than originally envisaged. The NTT testing also demonstrated the need for high level integration testing, and the Control Model will be used for that.

Fig. 2 below illustrates activities involved in testing/integration, and the places where the activities take place.

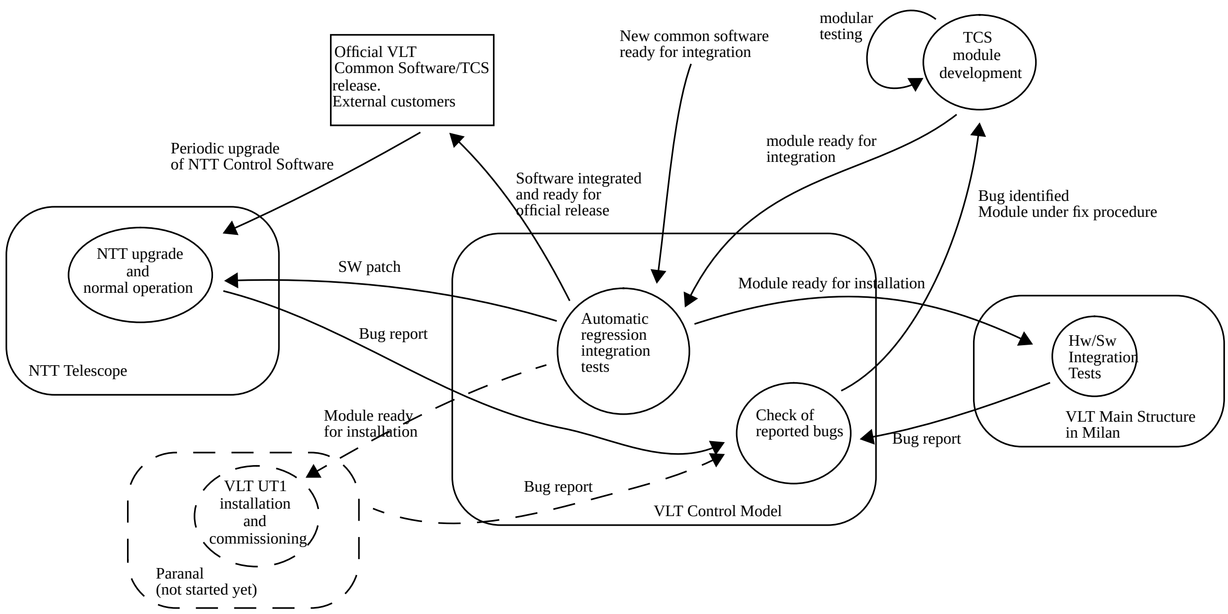

Fig.2: VLT Software testing strategy

Table 1 lists the most important TCS software modules and their actual development and testing status.

Module	Status	Tested on
TCS Interface. **User, engineering and instrument/application interfaces**	Complete for NTT. To be extended for VLT.	NTT, Control Model No problems expected in Milan
Presetting and mode switching. **High level WS coordination modules**	Complete	NTT, Control Model No problems expected in Milan
Tracking. **WS and LCU SW for tracking and pointing**	Complete	NTT, Control Model No problems expected in Milan
Axes control. **Low level LCU control software. Implements control loops for tracking (encoder read, motor control).**	Complete for the NTT Not tested for the VLT on real HW	NTT, Control model. HW dependent parts must be tested in Milan.
Enclosure control	Complete	Control model, Paranal
Auto Guiding	Small changes for VLT	NTT, Control model
Field Stabilisation	Under development	

Table 1: VLT TCS Software Modules - Present status

Module	Status	Tested on
Active Optics	Complete for NTT. To be extended for VLT.	NTT, Control model
Optics Control	Under development	
Adapter/Rotator	Under development	

Table 1: VLT TCS Software Modules - Present status

4. RELEVANCE OF NTT TESTS IN LA SILLA

The ESO NTT telescope in La Silla is the most important test-bed for the VLT Telescope Control System and for the whole VLT Operation concept.

During the last year the whole NTT Control System has been upgraded installing VLT electronics and software. The NTT Upgrade Project is described with much more details in another paper presented at this conference[7], but we want here to point out the importance of this project for the testing and integration of the VLT Control System.

The NTT allowed us to test on the sky:

- Integration of high level and LCU software in the real operational environment, i.e. with real network traffic, CPU load ant time constants.
- Synchronization of sub-systems via the GPS receiver and the time bus.
- Tracking and pointing algorithms, in particular for what concern the effectiveness of having completely independent tracking subsystems, synchronized via the time bus.
- Auto guiding and active optics algorithms and inter-operability, with the complete correction chain, including sky image acquisition via technical CCDs, correction feedback and M1-M2 corrections controlled by the active optics system.

It is also important to observe that this NTT testing period has allowed us to define and test:

- tuning procedures for control loops
- procedures for acquisition and evaluation of the pointing model

These procedures will make easier and faster the tuning of the first VLT telescope at Paranal.

Another important benefit of the NTT upgrade, that will become even more evident in the next months with scientific operation again going on, is the possibility of testing the whole VLT data flow model and operation procedures and, from the Control System point of view, the interfaces between TCS and high level observation software.

The same TCS User Interface developed for the NTT, with continuous feedback from the NTT Operators, will be used also for the VLT, warranting high usability level.

Paper [7] contains a detailed description of the NTT Control System, also showing the differences with respect to the VLT Control System.

5. THE VLT CONTROL MODEL IN GARCHING

The VLT control model in Garching resembles a complete VLT control system in terms of software and computers. It also includes some real VLT hardware components, like for example a complete Adapter/Rotator, a guide camera, an image analysis system and some test hardware replacements for real VLT components, like test motors and encoders, different from the real VLT ones but anyway extremely useful for testing purposes. Switchboards and function generators are used to emulate signals at LCUs digital and analog I/O boards, when no real hardware is available.

The diagram in Fig. 3 shows the components that are currently included or foreseen for the immediate future in the model.

The model is used to perform:

- Continuous automatic regression testing and acceptance tests for new releases of the basic VLT Common Software and of TCS[3] software.

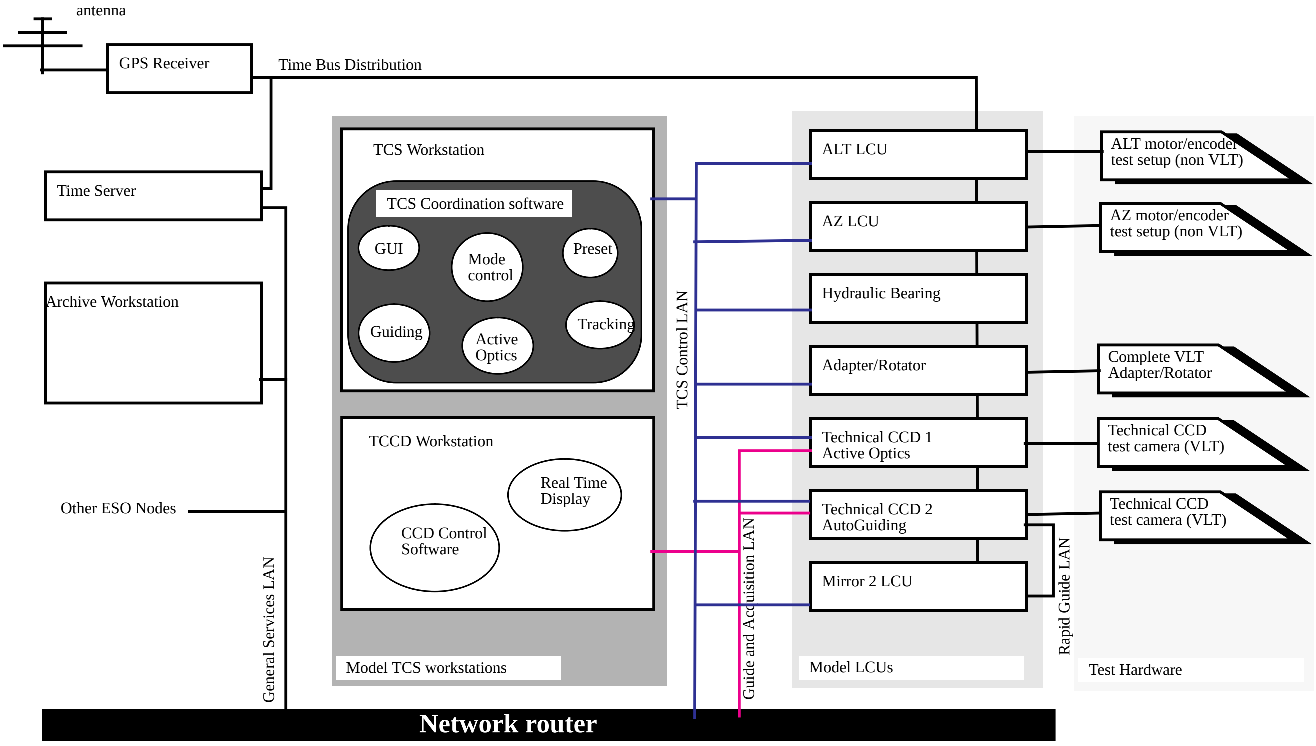

Fig.3: VLT Telescope Control Model - Present status

- Reproducing and debugging problems encountered at the NTT or in Milan.
- Running performance measurements and stress tests for the software, simulating networks failures, system loads or hardware malfunctions.
- Performing specific tests with the hardware components available only in Garching, like the VLT Adapter
- Performing simulation tests for new developments and algorithmic improvements of software modules, like Auto Guiding, Field Stabilisation and Active Optics.

It is also planned to install a test setup for the VLT ALT/AZ encoders, to be used for implementing and testing calibration and performance analysis software.

The following subsections illustrate briefly the results of the more recent tests performed using the VLT control model.

5.1 VLT Common Software Performance and Stress Test System

An important software module specifically developed for the VLT Control Model is the “VLT Common Software Performance and Stress Test System”[9].

This module has been designed to test and exercise performances of the main communication and data sharing components of the distributed VLT Control System, both on Workstation and LCU platforms:

- Message System - the message layer, used for interprocess communication and defining the command-reply protocol.
- On-Line Database - the real-time on-line database where all real-time and configuration data are stored at run time.
- Scan System - the high performance communication layer used to propagate and mirror LCU database information to control workstations.
- Alarm System - used to generate and propagate alarms on failure and critical error conditions.

The system produces performance statistics of these communication layers including data transfer rate, propagation time and CPU load under different system load configurations. One important matter of concern was the CPU load imposed on the LCUs by the heavy usage of the Scan System to mirror relevant parts of the database on the TCS control workstations. The tests have demonstrated that the real CPU load under realistic configurations is very low and therefore is not a real matter of concern.

It is also used to produce “artificial” load on specific system components in order to test the behaviour of TCS software modules under critical conditions. For example, it is used to pump up CPU load on specific LCUs, like the Auto Guiding LCU to test the Auto Guiding software under critical resource levels.

Detailed results of performance measurements are available in the Technical Report[10].

5.2 The VLT Adapter

The VLT adapters (4 adapters are ready and tested; another 2 will be ready in September) passed acceptance tests of the mechanics at the manufacturers site. The control system, implemented by ESO, is under development and test on a real adapter which was installed at ESO in April 1997, and will be available on the Control Model for tests up to when it is needed for the 4th telescope on Paranal.

Table 2 on page 6 shows the most important results for the hardware tests on Nasmyth Adapter Rotator Nr.3, performed last April. All parameters are well within spec. Position reproducibility will be measured again with higher resolution, since the maximum resolution available for measure at test time (1 pixel) was a factor 10 bigger than the specified value.

Performance verification for	Specified value	Measured value
SA Reference Unit:		
Position reproducibility	± 3µm	Within one pixel (see text)
Rotation angle	65˚	65˚
Instrument Rotator Drive Unit:		
Speed range	0 to 1.25 RPM	0 to 2.2 RPM
Tracking accuracy	2.6 arcsec rms	< 2 arcsec p-p
Maximum tracking velocity	±1500 arcsec/sec	> 1500 arcsec/sec
Adapter Drive Unit:		
Speed range	0 to 1.8 RPM	0 to 2.3 RPM
Tracking accuracy	2.6 arcsec rms	< 2 arcsec p-p
Maximum tracking velocity	± 1500 arcsec/sec	> 1500 arcsec/sec
Maximum disturbance torque due to cable wrap	± 40 Nm	< 40 Nm
Turntable:		
Speed range	0 to 8˚/sec	0 to 10˚/sec
Position accuracy	1.4 arcsec rms	0.6 arcsec rms
M4 Unit:		
Maximum positioning error	0.5 mm	0.3 mm

Table 2: Nasmyth Adapter Rotator Nr.3 - Performance Measurements

The adapter control software will be soon integrated with the other VLT TCS components for testing of tracking performances and for testing of the interfaces with Auto Guiding and CCD software.

5.3 Field Stabilisation and Rapid Guiding M2 correction performances

The Field Stabilisation system is meant to correct for tracking and pointing errors due to wind buffeting and atmospheric tilt effects.

High frequency corrections, with a sample rate of up to 100Hz in the most demanding case, are measured with the guide camera or by a scientific instrument and sent to the M2 tilt/chopping facility.

In order for this system to work effectively, it is necessary to have a very fast and reliable communication between the corrections producer and the M2 unit, in particular for what concern network latency and the time needed to deliver correction terms to the M2 unit.

The solution adopted on the VLT consists of a dedicated Ethernet LAN (the Rapid Guiding LAN) and a light communication protocol used to send corrections. An handshaking procedure ensures that only one sender and one receiver are at any time authorized to use the LAN, making the Ethernet de-facto deterministic. It has been measured an M2 maximum correction frequency of 500 Hz, with respect to a specified minimum value of 100 Hz.

This architecture has been implemented on the VLT Control Model and it is now under test, using the real Auto Guiding and M2 LCUs (in simulation mode, because M2 hardware is currently not part of the model) and control software.

5.4 The VLT Guide Camera

The guide camera is a technical CCD which is used as detector for Autoguiding and Field Stabilisation. The Control Model setup includes an optical device which produces a "guide star" that can be used to take images for autoguiding tests. Thus the autoguiding functionality can be tested with a close-to-real setup.

5.5 Image analysis.

The Control Model also has a complete Image analysis setup, including the CCD camera and a Schack-Hartmann device. With this setup, the complete Active Optics functionality can be tested, including sending corrections to the M1 and M2 subsystems, except that the loop is not closed, i.e. there are no mirrors and no measurement of REAL optics errors.

6. TELESCOPE STRUCTURE IN MILAN

Much of the high level TCS functionality has been tested on the NTT, within the NTT Upgrade project.

For this reason, the scope of the pre-erection testing in Milan has been slightly shifted. We have put more emphasis on characterization tests for hardware, low level electronics, drive and encoder performances and on the definition of tuning procedures. At the same time we put as much as possible of the effort for the integration of all subsystems on the NTT Upgrade and on the VLT Control Model.

In this way, we go to the Milan test period with an almost fully integrated control software, where a number of low level modules must be replaced by the actual VLT implementation and a number of coordination procedures have just to be slightly modified to take into account VLT specific requirements.

The telescope structure in Milan includes:

- TCS Workstation
- Complete alt and az LCU, drives and encoders
- Hydraulic Bearing sub-system

The test period foresees:

- Verification of all the interfaces, signals and interlocks with the real VLT hardware
- Characterization of the alt/az drive systems, with measure of the bode plot, close velocity loop at high and low speed, tuning of the PI controller with verification of the tuning procedures.
- Characterization of the alt/az encoders with requirements verification.
- Testing of the Hydraulic Bearing Sub-system
- Tracking and pointing stability and repetibility testing (obviously without sky!).

Measurements on the telescope in Milan are performed right now.

Table 3 shows the results for some important measurements done up to now on the telescope structure.

Performance verification for	Specified value	Measured value	Notes
Locked rotor frequency altitude	8 Hz	6 Hz (by AES)	Soil influence
Locked rotor frequency azimuth	10 Hz	6 Hz (by ESO)	Soil influence

Table 3: Measurements on Telescope Structure in Milan

Planarity azimuth tracks	1.0 mm	0.4 mm	
Max. run-out of azimuth axis	0.4 mm	0.1 mm	
Max. wobbling of azimuth axis	20”	10”	
Max. run-out of altitude axis	0.2 mm	0.16 mm	
Max. Wobbling of altitude axis	5”	3.5”	
Max. az. drive cogging torque	2% of max. continuous torque	0.3%	
Max. az. drive ripple torque	2% of actual torque	1.3%	
Max. altitude drives cogging torque	2% of max. continuous torque	0.5%	
Max. altitude drives ripple torque	2% of actual torque	1.5%	
Hydrostatic bearing stick friction azimuth	200 Nm	400 Nm	see text
Hydrostatic bearing oil film stability	0.1µm	0.1µm	
Encoder resolution	0.01 arcsec	0.01 arcsec	
Encoder repeatability	0.05 arcsec rms	0.05 arcsec rms	

Table 3: Measurements on Telescope Structure in Milan

The azimuth axis is now connected to the velocity controller and the LCU.

The hydrostatic bearing, in combination with direct drives, provide an unsurpassed low coulomb-friction (stick friction). The measured value is now 400 Nm. This measurement is still a bit polluted by non-friction effects like motor cogging.

With this low friction, it is possible to obtain a very good control of the tracking at low tracking speeds. Measurements done so far (in velocity control only) showed a well controllable speed down to 0.2 arcsec/sec. With a position loop closed, this number will be reduced even more.

The servo system implemented for the VLT consists of a cascaded servo controller, as described in [11].

The dynamic response of the azimuth velocity loop is shown in Fig. 4 below. This figure shows the response with very low proportional loop gain. Additionally, a 2nd order low pass filter is installed with a characteristic frequency of 8 Hz and a relative damping of 0.75. Purpose of the filter is to suppress peaks in the response at higher frequencies. These would cause instability when the loop gain is increased. Note that the phase in this plot has an offset of 180 degrees, due to the way of measurement.

Having this state reached, a measurement with sufficient loop gain can be done. This allows to resolve peaks and valleys at lower frequencies. The plot shows a well damped valley at 6 Hz (arrow on plot) and a peak at 9 Hz (arrow on plot). These are the lowest Eigenmodes of the structure in this measurement set-up. The values are lower than the specified ones; the reason is the influence of the soil in Milan.

The peak in this plot appears only to be marginally influenced by different positions of the telescope altitude axis. Therefore, the peak can be effectively cancelled with the technique described in [11]. There will be more influence visible in Paranal, where the concrete main mirror dummy will be replaced with the real mirror and cell, which have a relatively low Eigenfrequency.

Implementing a notch filter at 9 Hz allows to turn-up the loop gain. Up to now, a small signal bandwidth of 3.1 Hz have been achieved, as can be seen in the plot below(Fig. 5). This plot shows that there is still sufficient phase margin to increase the bandwidth.

Allowing integral gain and fine tuning of the parameters would result in a small signal bandwidth of approximately 4 Hz.

For what concerns encoders, tests are on-going. The resolution (0.01 arcsec) and repeatability (0.05 arcsec rms) meet specification. Calibration of the encoder is in progress and the measurement setup is at this moment modified in order to get time-correlation between the encoder measures and data from the calibration system.

A final test of the complete control software will include also all the high level control software.

It is interesting to note that the NTT graphical user interfaces are used, along with specific engineering user interfaces.

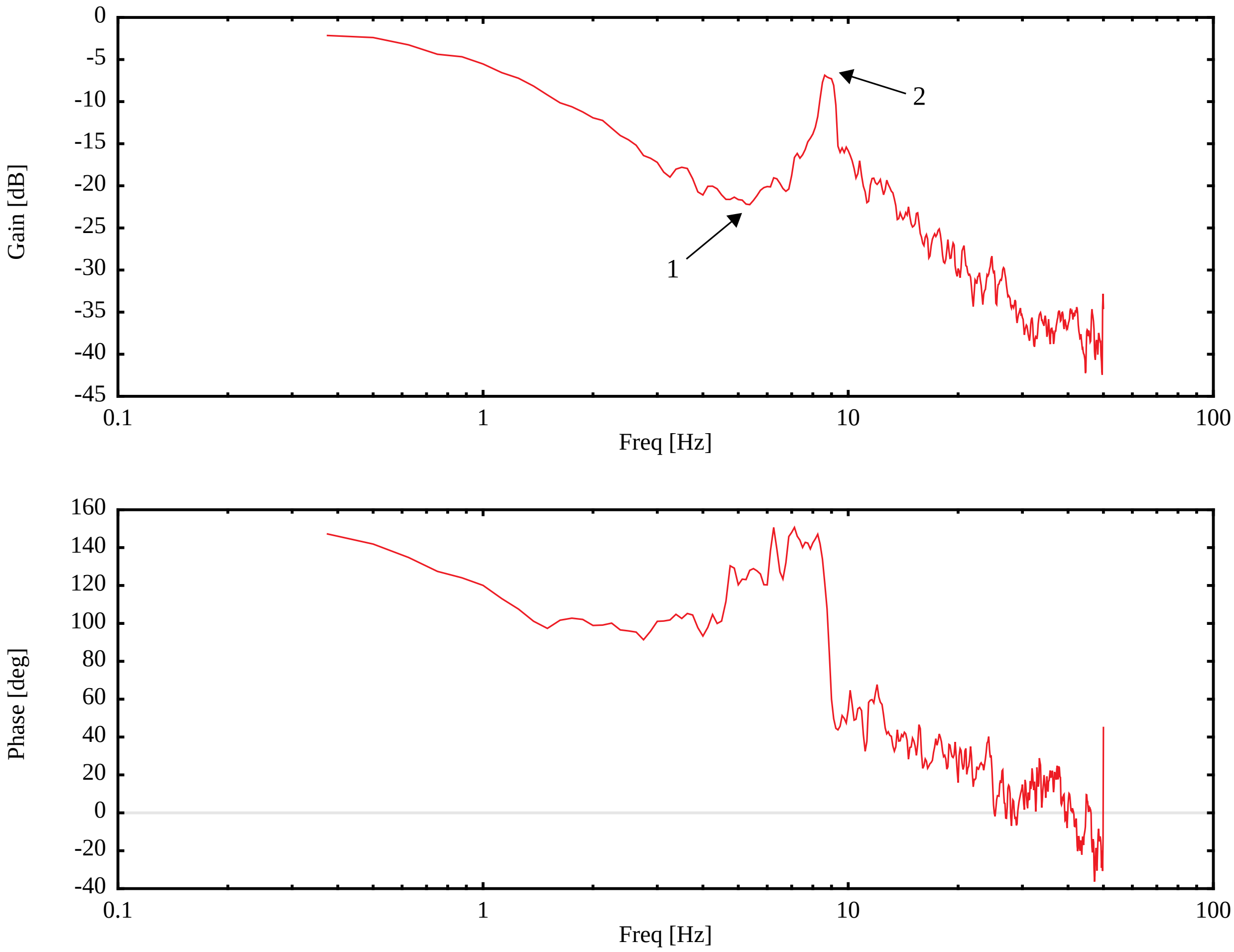

Fig.4: Dynamic response of azimuth velocity loop
with low proportional gain

7. OTHER SUBSYSTEM TESTS

7.1 Enclosure

The VLT enclosure systems, including dome rotation, are now being installed on Paranal, and the system for the first telescope is completed. The first part of the Acceptance Tests of the enclosures will be done 14-28 July 1997.The remaining part, including the daytime air-conditioning system, will be done later this year, when the telescope and all auxiliary equipment in the dome is completely installed.

The main components of the Enclosure system are: dome rotation, daytime air conditioning (temperature and pressure control), control of observation doors, ventilation doors and louvers (ventilation openings).

The main requirements to be met are:

- dome position accuracy 0.1 deg
- max temperature inside dome at sunset $T_{ref} + 1^{\circ}$
- cleanliness dust free (env class 30000)

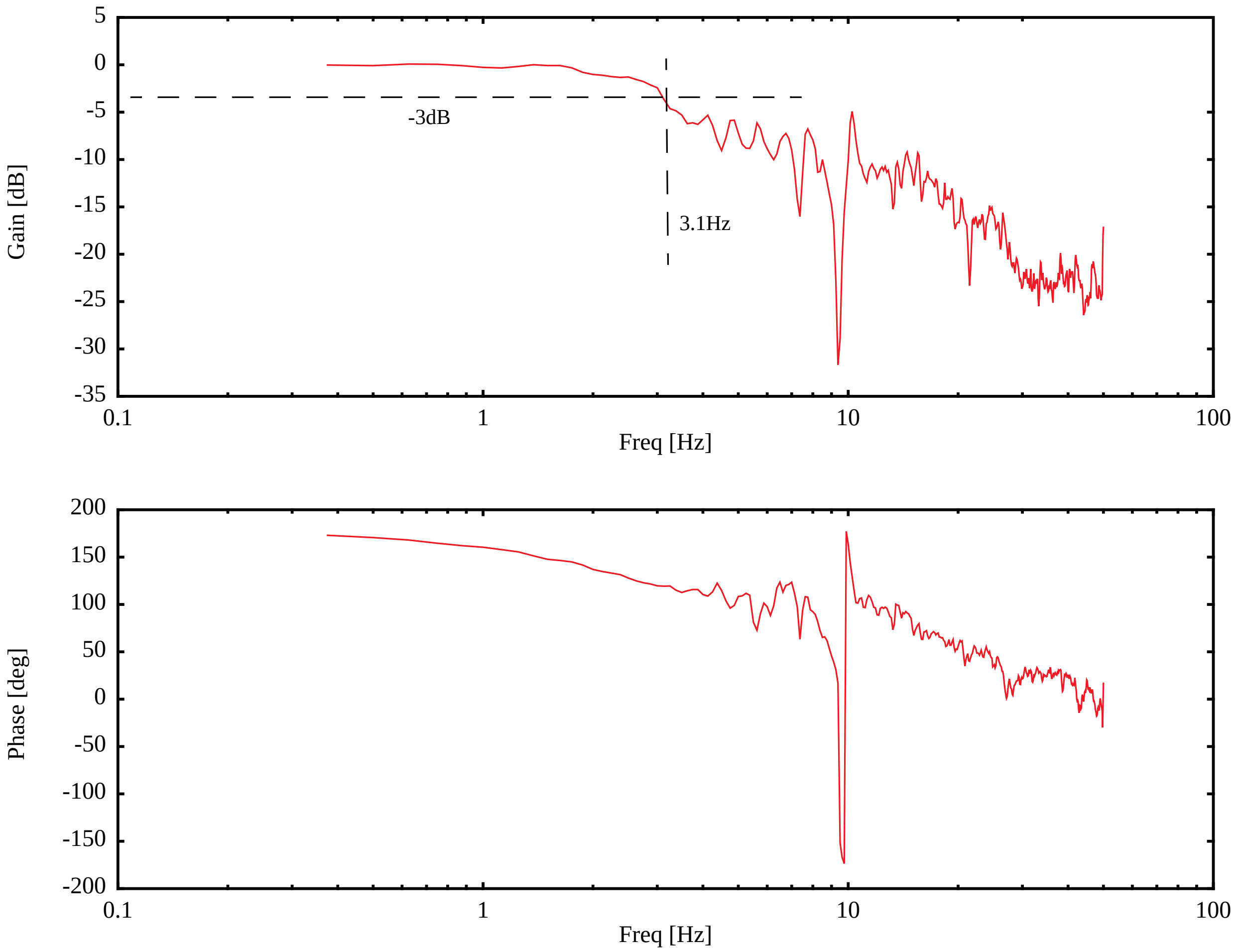

Fig.5: Dynamic response of azimuth velocity loop with notch filter
preliminarily tuned gain

- daytime over pressure inside dome 5 mm H_2O

7.2 M2 control system

The M2 unit consist of a 1.1 meter mirror and requirements for the control system are very high, since the chopping specifications foresee a chopping frequency up to 5Hz with a maximum amplitude of 2 arcminutes.

The M2 system control software has passed the Preliminary acceptance tests at the manufacturers site in Friedrichshafen, Germany.

The M2 unit, and the control hardware, is being tested right now. Basic requirements have been verified and the system is capable of sustaining a 5Hz chopping frequency with 2 arcminutes amplitude. Measured step response is 20ms, as required, and the closed loop bandwidth 70/80 Hz. Positioning accuracies of focusing, centering and tip/tilt are measured, and also the cross coupling between the different motion directions. The final results are not yet available, but the results achieved so far are quite promising.

7.3 M1/M3 support control system

The m1 cell and m3 tower subsystem (shortly called m1/m3) has been tested in France in preparation for the European readiness review, before delivery in Chile.

In particular the system makes use of 150 active supports, which in terms of control is translated into 6 Profibus segments and 150 VxWorks based microprocessors, all controlled by a VLT standard LCU. The tests have shown that the TMCs are capable of setting forces (in the range -500, 800 N) with a differential accuracy of 0.05 N and are capable of keeping them stable over time, according to requirements.

Tuning of various system parameters is still on-going before provisional acceptance at Paranal.

8. CONCLUSIONS

The integration of the VLT Telescope Control System is now in a very advanced phase and we are convinced we will be able to complete the system within the defined deadlines.

Testing of high level software was to a large extent done within the scope of the NTT Upgrade Project. For the VLT pre-erection tests in Milan, the emphasis is on electronics and low level software.

We have now a very stable high level software and all the basic concepts have been verified on the NTT or on the Control Model in Garching.

Still we need to perform, in the next months, a lot of tests in Milan on the low level software and we need to verify the performances of many hardware components, but the quantitative or qualitative tests performed up to now have not shown major reasons of concern. Among these, encoders performances accounts for the most important area of investigation. Once the calibration problems are solved, we are confident that we will get from the encoders the expected performance.

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

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