Proc. of SPIE Vol. 3352, Advanced Technology Optical, IR Telescopes VI, ed. L M Stepp (Jun 1998) Copyright SPIE

Design and Tests of the VLT M1 Mirror Passive and Active Supporting System

Thierry Hovsepian [1], Jean-Marc Michelin [1], Stephano Stanghellini [2]

[1] SFIM Industries, 13 Avenue Ramolfo Garnier, 91344 Massy, France
[2] ESO Karl Schwarzschild St 2 D85748 Garching bei Munchen, Germany

ABSTRACT

Keywords : Very Large Telescope, Active force control, Hydraulic supporting system design, M1 mirror position loop, M1 supporting dynamic behaviour.

1. INTRODUCTION

The french industrial consortium, SFIM Industries and GIAT, is in charge for ESO, since 1992, of the design, qualification, manufacturing, system integration and test of the complete VLT M1 Cell - M3 Tower sub-system.
In this frame, SFIM Industries, because of its experience in high technology systems including automatism, electro-mechanism and software, is responsible of the development, manufacturing and test of the Active and Passive Mirror Supporting System.

The VLT M1 Supporting System is implemented on the M1 Cell, developped and manufactured by GIAT Industries. The M1 Cell is attached to the telescope main structure by twelve flanges.

The M1 Supporting System performed the three main following functions :
- M1 mirror weight supporting, whatever the VLT main structure inclination,
- M1 mirror positioning inside the M1 Cell, along six degrees of freedom,
- M1 mirror optical surface tuning.

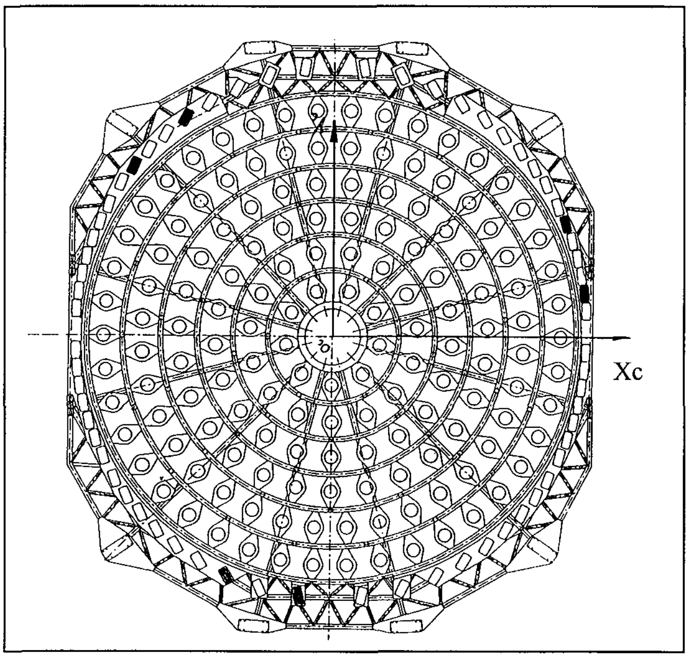
The objective of this paper is to describe the design and the level of performance recorded during tests performed in Europe and Chile, on the first M1 Cell - M3 Tower unit.
Three main items will be considered :
- The M1 Passive Supporting System (**PSS**), which performs the lateral and axial M1 weight supporting and positioning,
- The Active Axial Support (**AAS**), which tunes the optical M1 surface,
- The Axial Supporting System (**ASS**), including active and passive axial supports, which characterises the performance of M1 optical correction.

2. M1 MIRROR PASSIVE SUPPORTING SYSTEM (PSS)

2.1 PSS PRESENTATION

The VLT supporting and positioning system is based on 150 axial and 64 lateral hydraulic passive supports, grouped in 3 piping networks in axial direction and 2 piping network in lateral direction. This hydraulic supporting system has two main functions : supporting the mirror weight whatever the VLT main structure inclination and to assure the positioning of the M1 mirror inside the M1 Cell along 5 degrees of freedom.
The PSS is composed of 2 main sub-systems : Passive Axial Supporting System (**PASS**), and Passive Lateral Supporting System (**PLSS**) respectively in charge of mirror weight axial and lateral component and providing axial and lateral stiffness. Because of operational and maintenance using mode, the M1 mirror has to be inclined between 0 and 70° (operational) and even 91° (maintenance). During inclination, the mirror weight is transferred from PASS to PLSS.

2.2 PASSIVE AXIAL SUPPORTING SYSTEM (PASS)

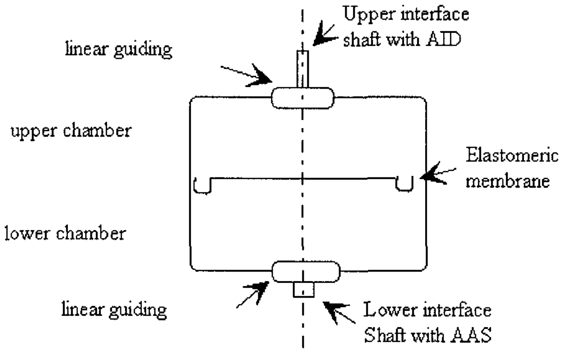


The PASS functional requirement can be summarised in 3 main functions :

- supporting axial component of mirror weight (M1 weight ≈ 23 tons),
- positioning M1 mirror with respect to the M1 Cell,
- ensuring the compatibility with active force pattern provided by Active Axial Supports (**AAS**) (see § 3)

PASS is composed of 3 identical hydraulic sectors A, B, C at 120° Each hydraulic sector contains 50 Passive Axial supports (**PAS**), all connected by an hydraulic circuit called Whiffle Tree (**WT**) and an electro-hydraulic actuator called Volume Adjustment Unit (**VAU**). So, the M1 mirror is axially supported on 3 equivalent points located at the barycenter of each hydraulic sector allowing not to bring constrains on the mirror body.
The PASS contains 150 PAS distributed under the M1 mirror in 6 concentric rings.

Each PAS is associated to an Axial Interface Device (**AID**) . The AID takes place between PAS and the M1 tripod glued on the back side of the M1 mirror, defining the 150 locations of supporting. The AID function is, on one hand to transmit the axial mirror weight component to the interface shaft of PAS and in the other hand to transmit the AAS force correction map to the mirror.
The AID assumes the force to be axial with minimising lateral spurious effort on the mirror. Moreover, the AID allows to compensate the alignement of PAS with respect to mirror interface tripod.



Each PAS consists in :

- a fixed part assembled on M1 Cell, on which the AAS body is assembled too,
- two internal hydraulic chambers filled with oil
- a mobile part including upper and lower interface shafts respectively with the AID and the AAS shaft applying the active force.

The two hydraulic chambers act in opposite directions on the mobile part. The main chamber supports the weight of the mirror. The compensation chamber pre-stress the first one and compensate the oil volume column. The both hydraulic chambers are closed by elastomeric membranes

To achieve the requirement of force accuracy of the PAS and transparency of the active force delivered by the AAS, the elastomeric membranes and the mobile part guiding components are selected with respect to their stiffness and friction characteristics.

2.3 PASSIVE LATERAL SUPPORTING SYSTEM (PLSS)

The PLSS is composed of 2 identical hydraulic sectors D and E at 180°. Each of them contains 32 Passive Lateral Support (**PLS**), all connected by an hydraulic circuit called lateral Whiffle Tree (**WT**) and an electro-hydraulic actuator called Volume Adjustment Unit (**VAU**). The PLSS is containing 64 PLS distributed symmetrically on the edge of the mirror. On each sector, half of the jacks push the mirror since half pull the mirror.
The M1 mirror is laterally supported on 2 equivalent points located at the barycenter of each hydraulic sector. In order not bringing twisting effect, the force applied by the PLS+LID assembly is along the neutral fibber of the mirror.

Each PLS is associated to a Lateral Interface Device (**LID**). The LID takes place between PLS and the M1 PAD plugged in the edge of the mirror defining the 64 locations of supporting. The LID function is to transmit the lateral mirror weight component to the interface shaft of PLS with respect to the direction of lateral force.

In a same sector each PLS/LID has different action directions and produces a force which is described by three components : axial, radial and tangent. The global forces of each PLS, which is the quadratic sum of these three components, are equal in a same sector when the PLS are mounted on plate boxes welded to the primary mirror Cell, and when the LID is able to be oriented in the direction of lateral force action.

Each PLS is composed by a two chambers hydraulic, a mobile part and a fixed similar to the one used in the passive axial supports. The mobile part is guided laterally by a low friction device. The mobile part acts on an angle bracket which rotates around a perpendicular axis. The moment arm is adjustable in order to achieve the accuracy of the lateral force of each support. On the other extremity of the angle bracket is fixed the Lateral Interface Device which transmits the load of the mirror along the dedicated direction.

2.4 STATIC AND DYNAMIC STIFFNESS

Other major requirements affect the PAS and PLS :

- M1 position stability when mirror altitude angle changes.

This is mainly assumed by static stiffness of PAS+AID for axial direction and PLS+LID for lateral direction. PAS and PLS static stiffness is determined by :

- stretching of the hydraulic jack membranes
- swelling of the piping, VAU, accumulator and other hydraulic parts,
- deformations of the mechanical parts between central shaft and interface flange with M1 Cell, ...

The stiffness between each hydraulic sector barycenter and the M1 Cell (considered as rigid body) is greater than 5 10^8 N/m for axial and 2 10^8 N/m for lateral supporting, whatever the operational altitude angle of the telescope (0 to 70°).

- M1 Mirror/M1 Cell first eigen frequencies.

This is mainly assumed by PAS, PLS and M1 Cell dynamic stiffness. Difference between static and dynamic stiffness is because of in static case, there is no oil motion in pipes.
Assuming that hydraulic jacks are isolated from the oil circuit, the dynamic stiffness between central shaft and mechanical interface on M1 Cell is greater than 5 10^7 N/m for axial and 3 10^7 N/m for lateral supporting in order to obtain first axial eigen frequency around 25 Hz

- Stability of passive forces when the telescope and all other sub-systems are motion less.

The stability error takes into account the static drift due to the stress release, membranes creep or spurious behaviours
Stability of passive force effectively applied to the mirror is better than 0.05 N over 1 minute.

2.5 DESIGN OF THE WHIFFLE TREES

Two types of Whiffle Tree (WT) have to be considered according to the PLSS and the PASS (see §2.2 and 2.3)

The static function of the WT is to equalise the pressures in all the PAS (and PLS) of a same sector, in both main and compensation chambers, if we except the part of static pressure due to the hydraulic column weight. This function is necessary to support the mirror in an isostatic way. The physical characteristics of the WT pipes have to be taken into account to assess the static stiffness of the hydraulic sector.
The WT has also other dynamic functions :

- to allow the motion of oil between the Volume Adjustment Units and each of the 50 PAS (and 32 PLS), when the Mirror Position Loop is powered on,
- to allow oil displacement between the PAS of a sector, when active axial force patterns are applied through the PASS,
- to provide damping effect to the dynamic mirror motions.

The analysis of these both dynamic functions at system level and the optimisation of the compromise between Settling Time and Damping, leads to definition of the piping architecture and pipes physical characteristics.

The oil piping is optimised in order to find the best dynamic compromise between settling time and damping. Moreover, optical aberration correction requires that PASS does not disturb the force pattern applied by AAS. This requirement can be seen from 3 aspects :

a) static frequency : active force applied is transmitted without modulus variation,
b) dynamic frequency : dynamic of the force pattern has not to be faded by PASS,
c) PASS internal dynamic not to excite M1 mirror/M1 Cell coupled system eigen frequency.

To answer to these points, a dynamic simulation study was performed. The optimisation variables are WT topology (number of pipes and connection geometry), the rigid pipe diameter and the flexible pipe diameter connecting PAS to the rigid pipe. This optimisation was performed considering 2 types of optical correction : Astigmatism (**AST**) and Spherical Aberration (**SPA**). For the point c), it has been verified that force pattern does not excite the M1 Mirror/M1 Cell modes.

Two limit cases of behaviours was considered : low and high inertia line model :
- *Low inertia model* : in this case (high pipe diameter and high connectivity of WT topology) PAS are all coupled. Due to high coupling, the settling time is low but damping is also low.
- *High inertia model* : in this case (low pipe diameter and moderate connectivity of WT topology), PAS are dynamically uncoupled. Due to low PAS coupling the damping is high but the settling time is high.

The best compromise have been found as :
- inertial and dissipation : for the axial whiffle tree, 12 mm rigid pipe and hose internal diameter ensuring reduced settling time with acceptable damping ; for the lateral whiffle tree, 8 mm internal diameter to have a good compromise between physical implementation constraints (routing, weight, ...) and community with the axial supporting system (the dynamic simulation takes only into account the axial supporting system).
- topology : for the axial whiffle tree, triple loop (4 ring pipes) ensuring good oil circulation and appearing as the best compromise settling time/complexity ; for the lateral whiffle tree, one pipe only.

The piping architecture is as following :

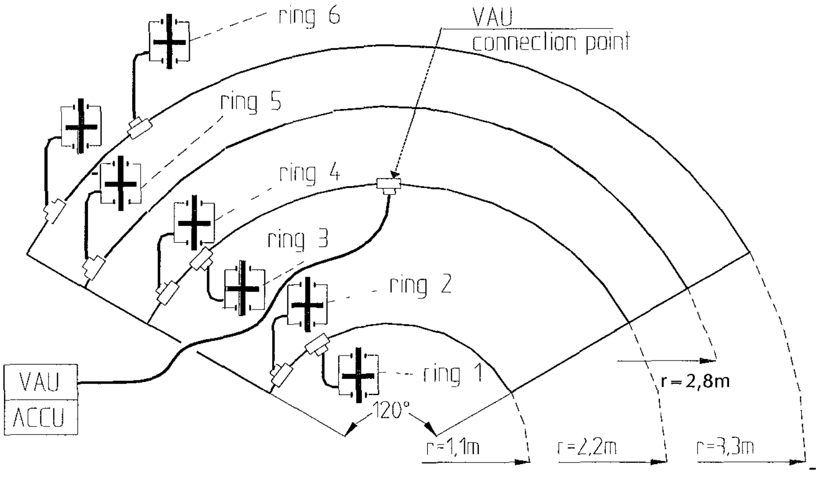


Figure : Triple loop architecture for axial sector

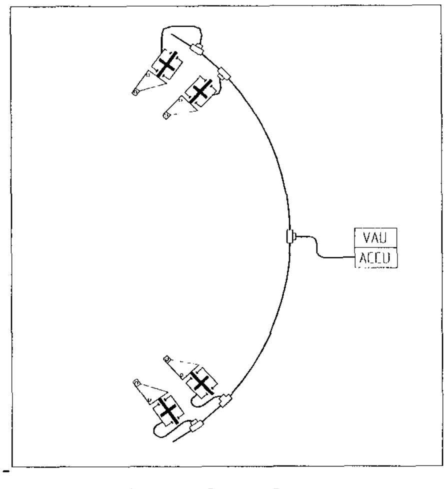


Figure : lateral sector

With these values, we obtain as simulation results in both cases 0.7sec of settling time (95%) with a quite good damping. Experimental results are presented in §5.

2.6 SIX WHIFFLE TREE

Objective :

To reduce the effect of wind buffeting on M1 mirror, by coupling it to the mirror cell, at least for certain modes (astigmatism), it is proposed to divide each whiffle tree in two parts, to create 6 virtual points for the M1 mirror supporting (three additional points).

The supporting system can be modifiable between two different limit whiffle tree configurations :

- a 3 whiffle tree configuration (at 120°, each one with 50 axial supports)
- a 6 whiffle tree configuration (at 60°, each one with 25 axial supports)

The modification of configuration is performed by using valves, controlled by the LCU.
The control of the opening/closing of the valves shall allow to modify the level of connectivity between each half sector. In the fully open state of the valves, the system shall be equivalent to the baseline configuration (3 sectors).

Design driver

The design of this concept has been based on a dynamic simulation of the behaviour of the supporting system. In this frame, it has been modelized by three sectors of 10 supports which may be divided per two (isolation) becoming 6 sectors whiffle tree. The representative active force patterns used, were the astigmatism correction maps. A dedicated wind disturbancies modelization has been taken into account (astigmatism load case 2,5Hz) : $\mathbf{F_{ij} = F \times \rho_i^2 \cos(2\varphi j + \theta) \times \sin\omega t}$

The conceptual choice of valves was to put one of it on each hydraulic pipe of a sector, controlled individually, to allow a step by step tuning (4 pipes = 16 combinations OPEN/CLOSED).
The characteristics of the valve selected are :

- no oil volume variation during the motion of the valves (closed / open)
- integral circulation of oil when valve is fully open ; mini internal diameter 12mm (bi-directional)
- quick motion of the throttle : lower than 30ms (electro-pneumatic ; idle and safety state = open)

Simulation results

a) - The comparison of the results obtained between the 3 sectors whiffle tree configuration (4 valves open) and the configuration where only the internal ring valves are opened, shows that :
- the cutting frequency range (half of M1 displacement) is :
1,7 Hz to 0,6 Hz
- the settling time after an astigmatism map of active forces application is :
0,5 second to 1,5 second

b) The addition of a calibrated bypass in parallel with the internal ring valves, allows to increase these ranges to :
0,23 Hz and 5 seconds.
The bypass choose is a tube of 4 mm internal diameter (compared to 12 mm for the whiffle tree) and 0,40 m length.

Test results

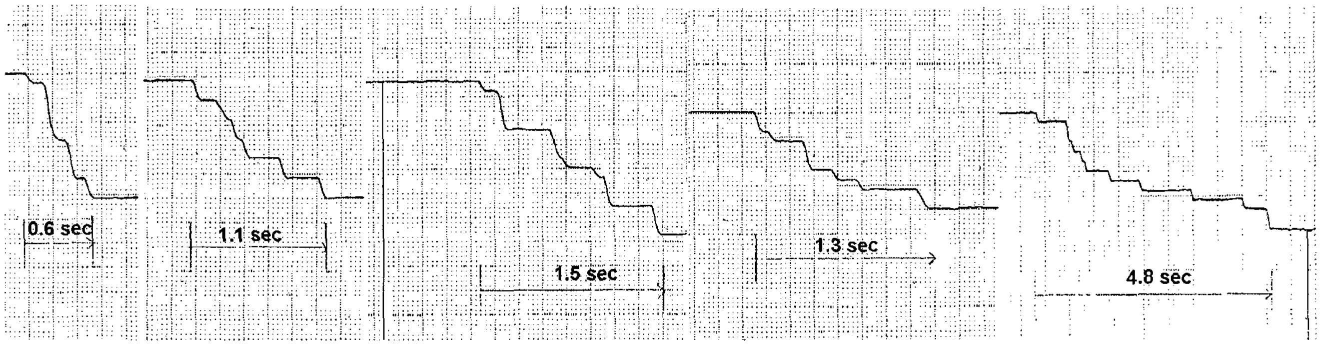
- During the system integration and validation test , in Europe and Chili, various configurations of whiffle tree tuning have been tested.
- The tests consisted in the application of an astigmatism map of active forces on the 150 AAS, and the recording of the behaviour of the active force applied on the mirror (measurement done at an AID level, equipped by a loadcell) and the motion of a peripheral point of the M1 mirror (measurement done by a laser displacement sensor).

The recording confirm the compliance with the dynamical simulation results

Valves configuration	**settling time for a 2N step astigmatism 0° map**	
	simulation results	measurements
all valves open	0.5 sec	0.6 sec
only intermediate valves V3 open	-	1.1 sec
only intermediate valves V2 open	-	1.5 sec
only internal valves V1 open	1.5 sec	1.3 sec
all valves closed	5 sec	4.8 sec

The intermediate configurations are equivalent, in term of settling time, to the case where the internal ring valves are opened.

The following recording of M1 mirror displacements with respect to the valves various configurations illustrate the above results



2.7 M1 MIRROR POSITION LOOP WITH RESPECT TO M1 CELL

The Passive Supporting System have to ensure the M1 mirror positioning with respect to the M1 Cell in order to equalise M1 and M2 mirror optical axis. The reference frame of M1 positioning (Oc, Xc,Yc,Zc, α, β, γ).
The PASS allow to control Zc, tilt α and β. PLSS allow to control Yc
Gamma corresponding to optical axis could be controlled but has no impact on the telescope. Xc can't be controlled due to PLS configuration. Nevertheless, Xc is maintained by dedicated devices called Lateral Restraining device (**LRD**) which provide stiffness along this direction.

In the positioning function, M1 mirror is considered as a rigid body set on 5 virtual fixed point coinciding with WT barycenters of the 5 axial and lateral hydraulic sectors.

A servo loop called M1 Positioning Loop (MPL) was studied and implanted to meet positioning function requirement. The MPL is composed of 3 main parts : actuator system, sensor system and software control loop.

2.7.1 Volume Adjustment Unit (VAU)

The control of the oil volume of each hydraulic zone is achieved by a motorised piston or pump, called Volume Adjustment Unit or **VAU**, able to add or remove some oil from the main circuit. The mechanism of the VAU has to be irreversible in order to limit power consumption, apart during mirror positioning phases. The VAU is the actuator of MPL.
The VAU is able to ensure a full stroke displacement of the PAS and PLS.

To achieve its own control loop performance (for axial : 20 µm differential accuracy along the +/-10mm operational stroke, within 12 sec settling time), the VAUs contain the following sensors :
- an absolute position sensor with a measurement stroke equivalent to VAU full stroke (for axial +/-50mm)
- an angular position encoder to compute the motor speed

For safety reason the VAU is equipped with an analogic pressure sensor able to monitor pressure variation inside the VAU. The hydraulic connection with the WT is performed through an isolating valve, to increase the static stiffness of the WT.

VAU is internally controlled and receive positioning command from the MPL. The VAU control loop is non linear because of dry friction of the screw-nut system which ensure the mechanical irreversibility. VAU stroke and accuracy achieving M1 mirror requirement depend on section ratio between VAU piston and the equivalent jack of 50 PAS or 32 PLS located at the barycenter of hydraulic sector.

2.7.2 Mirror Position Encoder (MPE)

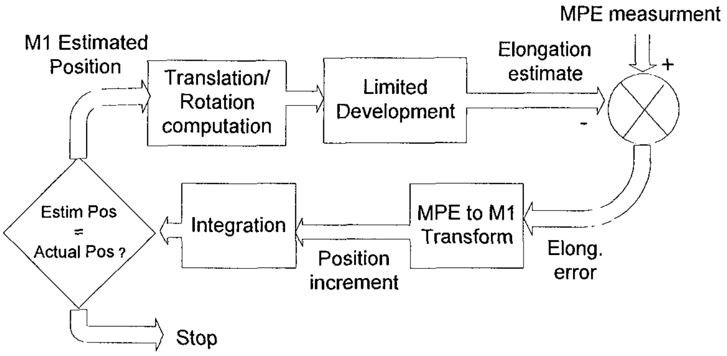
The M1 mirror sensor system is composed of 6 MPE distributed around the mirror and measuring the M1 motion wrt the M1 Cell.
MPE is a ballbar sensor which consists in a tube made in invar, containing an accurate LVDT (Linear Variable Displacement Transducer) with at its ends two magnetic spheres. These spheres are maintained by two magnetic cups, one

linked to the mirror and one linked to the M1 Cell, ensuring an isostatic contact. The operational stroke is 10mm with 0.6µm of resolution. Each MPE is associated to a local electronic box ensuring signal demodulation and RS485 communication protocol. All MPE are connected in a network and send information to the Local Control Unit (**LCU**) containing the control software.

MPE measuring is absolute because the mirror is periodically removed if the M1 Cell to be aluminised So, we can recover the M1 position without initialisation step.

2.7.3 Linearised Stewart Model

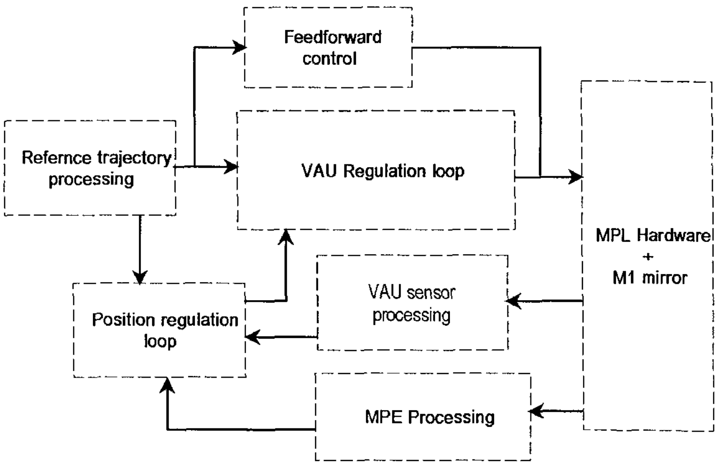
M1 mirror position has to be provided in the reference frame. But MPE located at the mirror periphery only perform a measurement of their own elongation. So, the M1 position has to be reconstructed on the basis of the 6 MPE elongation measurements.
This is obtained by a linearised version of the Stewart model known in robotics.
Due to the fact there is no direct transformation giving the mirror position in the reference frame when measuring elongation, we have to perform an iterative computing model which converge towards the actual M1 mirror position.



The MPE computing model can be seen as control loop adapting the M1 mirror estimated position to the MPE measurement through inverse transformation which gives the MPE elongation versus the M1 position.
The usual Stewart model has to consider some assumptions on the symmetry of the problem which are not needed in our linearised version based on limited development of estimated elongation.
MPE resolution allows to obtain 0.1 µm resolution for translation (Yc, Zc)and 0.05 arc second resolution for rotation (tilt α and β).
Software implementation has been optimised in order to achieve in order to achieve real time computing (including MPE estimation model convergence) with 100 msec of sample period.

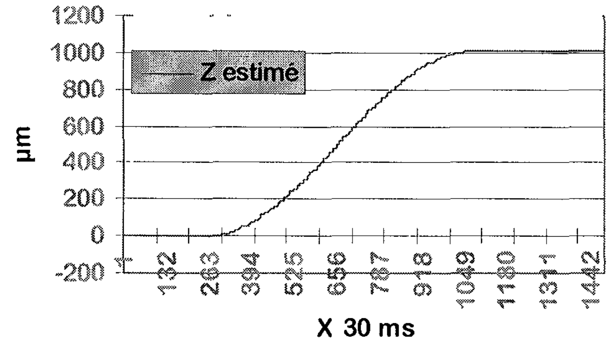
2.7.4 MPL Architecture

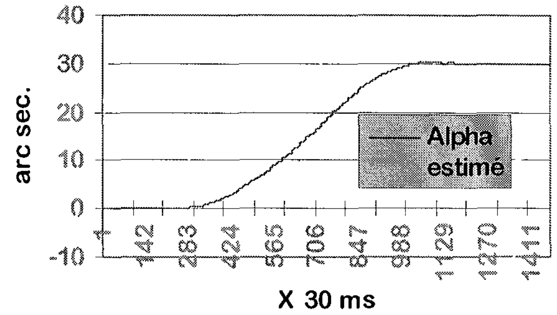
The MPL is organised in a hierarchical structure decomposed as follows :



a) Reference trajectory generation module including M1 to VAUs transformation model. This module computes VAU and M1 trajectory in order to have a good compromise step size/settling time and not to excite M1 Mirror/M1 Cell eigen frequencies,
b) VAU internal control loop driving the VAU piston location, including prepositioning phase due to isolating valves between VAU and WT. Then, if altitude change, pressure of WT and VAU can not be the same. So, a prepositioning phase ensure pressure equalisation before opening valves.
c) MPE estimation model providing M1 mirror position estimate (cf. 2.7.3)
d) Position global regulation loop ensuring a good dynamic behaviour of all the degree of freedom and compensating errors due to VAU model imperfections.
e) MPL Scheduler monitoring each phase of M1 motion operation. The scheduler synchronized allows to control the 5 VAUs simultaneously in order to reduce the operation time. Large motion are performed in less than 30 sec.

2.7.5 Experimental results





The MPL allows to achieve the commanded M1 position within the requirement of range and accuracy :
Yc and Zc translation : range : ± 1000 µm, accuracy : ± 5 µm
tilt $\alpha$and β rotation : range : ± 30 arc second, accuracy : ± 0.2 arcsec

3. ACTIVE AXIAL SUPPORT (AAS)

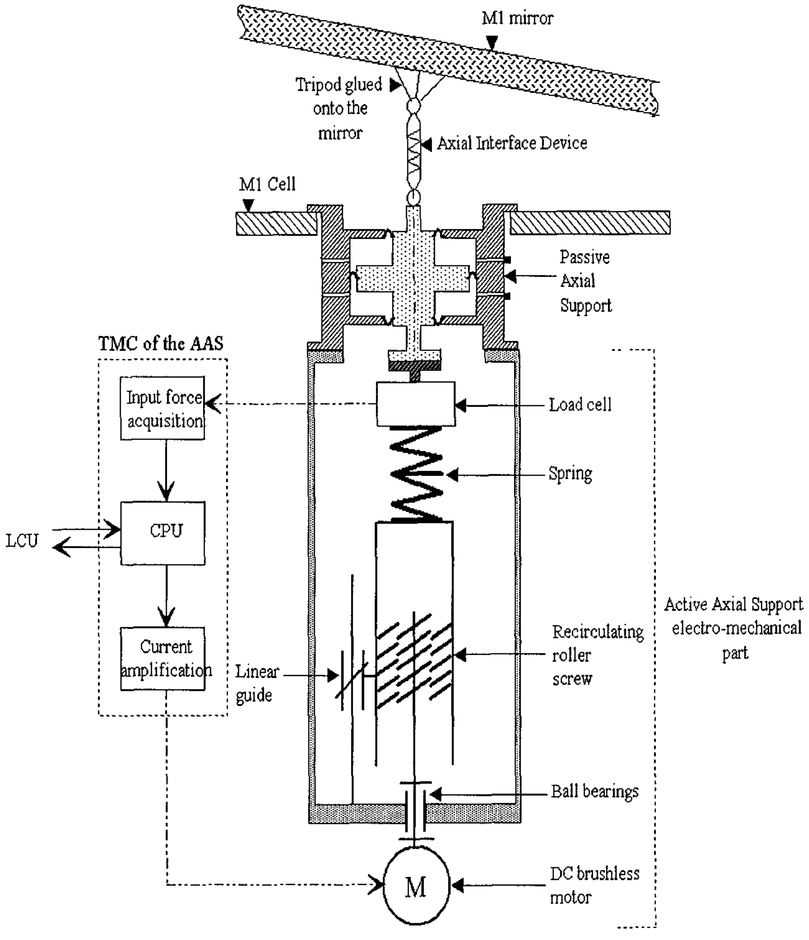
3.1 INTRODUCTION

The Active Axial Support is the main equipements involded in the optical M1 tuning function.
It is an "intelligent" electromechanical jack used to apply a constant positive or negative force on its central shaft coupled to the PAS, according to a setpoint value commanded by the Local Control Unit (LCU) of the "M1 Cell - M3 Tower".
The Active Axial Support manages its own operation and safeties independently. It answers to the commands sent by the LCU, and provides to the LCU status reports in return.
All dialogue with the Local Control Unit is via a PROFIBUS type field bus.
There is 6 group of 25 AAS connected to 6 independant LCU Profibus Hardware drivers. All these 150 supports constitute the Active Axial Supporting System (AASS).

3.2 ACTIVE AXIAL SUPPORT DESCRIPTION

The Active Axial Support is a monobloc assembly comprising an electromechanical part and an electronic part, also called Target Micro Controller, or TMC (see figure).

The electromechanical part consists of a motor, a special screw-nut system, a spring and a load cell. The motor drives the screw, the screw-nut system converts rotation into translation and demultiplies the movement, the spring converts translation into force, and the load cell directly connected to the mobile part of the PAS measures the final force produced by the AAS and enables the servo loop to be closed. The operation of the Active Axial Support is compatible with operational working of the PAS, in particular with its axial movements (+/-5mm PAS stroke).



The control electronics TMC, can be split into five parts:
- the CPU ("Intelligent Universal Controller" (IUC system, stand alone version of the VME standard) from PEP Modular Computers Gmbh.,
- the I/O interfaces for the load cell acquisition chain (18 bits resolution, equivalent to 0 005N) and the temperature probes,
- the motor power amplifier,
- the power supplies,
- the mother board supporting the interconnection and the Profibus hardware drivers (RS485).

The TMC Software is in interface with the LCU on the PROFIBUS network ; it provides digital slaving of the force loop, it manages and tests AAS operation, it provides AAS safety functions and contributes to M1 mirror safety. Each TMC is identified by a PROFIBUS address, given at integration into the "M1 Cell - M3 Tower" assembly and used to locate its geographical position.

A cover houses the electromechanical and electronic assembly and handles thermal exchanges, with the M1 Cell system equipments.

3.3 ACTIVE AXIAL SUPPORT FUNCTIONALITIES

3.3.1 Dialogue management between LCU and TMC

It is managed by PROFIBUS :

- the HW is defined by the PROFIBUS standard. Via the fieldbus, each TMC can be initialized, receive commands, start, stop and synchronize programs, receive parameters, send status and exchanges information with LCU.
- the frame rate is lower than 0,2 s in Send and Receive Data mode, and around 20ms in broadcast mode,
- the frames format is defined by successive dedicated data blocks sent and receive : identification block, force value, test datas, test/error reports (failure, warning)
- the TMC Software and the specific AAS parameters are downloadable via Profibus, in the TMC EEPROMs

3.3.2 Control of active force

The TMC software allows two differents operating modes :

- Standby mode : there is not motor current commanded, so no active force applied ; TMC is power supplied
- Active mode / test mode : application of operationnal force range (-500 N → +800 N) with the achievement of Differencial Force Setting Accuracy and Absolute Force Accuracy

3.3.3 Triggered test

TMC software foreseen embedded tests triggered by the LCU to check the AAS functionnalities :

- preliminary tests (RAM, EPROM, EEPROM)
- control loop test : analyse of the response to an active step of force (overshoot, pseudo period, error)
- motor amplifier watchdog test : simulation of a refresh missing of the amplifier command,
- sampling test : TMC send to LCU a sample of data measured with a specific period

3.3.4 Data supervision

The purpose of this function is to communicate to the LCU any failure detection and warning characterizing degraded modes.

- failure detection : bad contents of memories, force measure or motor current out of range, power amplifier watchdog
- warning detection (degraded mode) : communication errors, no coherence between force measured and current command, current measured and current command, Load Cell or electronic boards temperature out of range, power supply default, PAS end stroke switches actived

3.4 ACTIVE AXIAL SUPPORT TECHNICAL PERFORMANCES

The Active Axial Supports achieves the following performances :

a) It produces a constant force within the range : **-500 N < Factive < +800 N,**
where the negative sign indicates that the active force is deducted from the passive force, with the AAS exerting traction on the PAS shaft ; the LCU sends to each AAS the force setpoint as a relative or an absolute value.

b) the force servo loop performances are :

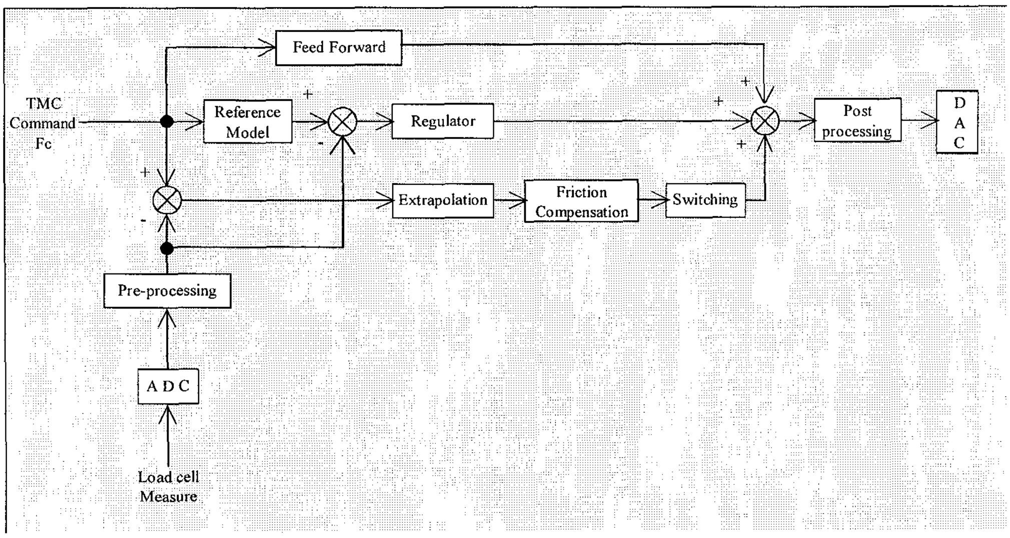
-	**interval time to modify active forces of the 150 AAS, for a 2N step :**	< 0,3s
-	**Average force variation speed :**	**> 50 N/s**
-	**Absolute force accuracy (AFA):**	**± 1 N**
-	**Differential force setting accuracy (DFSA), for 10 N step :**	**± 0.05 N minimum**
-	**Settling time for 2N (10N) active force steps (accuracy = 0.1N)**	**0,3 sec (1 sec)**

c) Stability (at constant zenithal distance, without PAS central shaft displacement) :
better than 0,05 N over 1 minute ; better than 0,1 N over 10 minutes

d) Power consumption : **8w maximum mean value for the 150 AAS**

e) AAS cooling by heat draining, to the AAS metallic cover linked to 2 heat pipes, to allow a **difference of temperature between the ambient air and the external face of the AAS cover** : **+1,5° / -5°.**

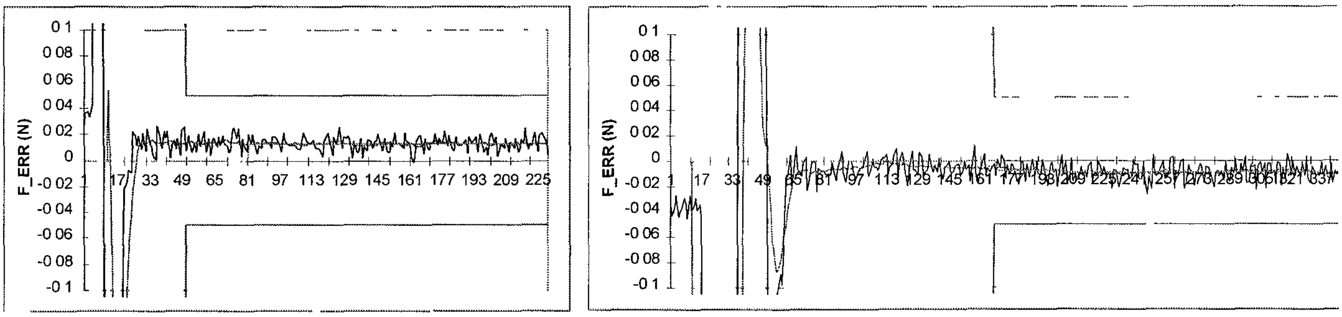
The AAS control loop design is based on a principle of friction torque non linear compensation.



The control algorithm consist in the following elements :
- a pre processing : it is used to prepare the datas for processing (format, filtering, conversion...),
- a reference model : it defines the desired response to a step command, in term of settling time, overshoot and convergence time,
- a feed forward control : it assume that the transfer function between the force command and the force actually applied is as close as possible to 1. It acts on the motor with anticipation to regulate the error signal instead of the force command.
- a regulator : it regulates the difference between the reference model and the actual behaviour of the AAS
- a friction compensator : it provides enough control to overcome the friction torque of the mechanic

3.5 ACTIVE AXIAL SUPPORT PERFORMANCES TEST RESULTS

Unitary acceptance test are performed at the end of the manufacturing, at SFIM Industries premise. These automatic tests, drive by computer, allow to issue individual acceptance test reports which demonstrate the compliance with the technical requirements.
Various steps of 2N and 10N are recorded and analyze during acceptance tests, to evaluate the quality of each support. Such following graphs are obtained and computed :



2N/10N step of active force : The Force error (Fmeasured-Fcommanded) is traced inside the required template
The time scale is trace with respect to the CPU software interruption rate = 1/150 sec (for 2N : 49 IT = 0,3 sec) (for 10N : 150 IT = 1 sec)
In addition to these unitary tests, SFIM Industries has performed complementary acceptance tests in Europe and Chili, with all the 150 AAS assembled on Passive Axial Support, inside the M1 Cell, and connected to the LCU.
The Differential Force Setting Accuracy, the settling time, the stability performances have been confirmed on the complete group of 150 units. Furthermore all the operational functionalities (force command, dialog, doawnloading, monitoring, ...) have been validated through LCU command.

4. M1 MIRROR AXIAL SUPPORTING SYSTEM (ASS)

In addition to the AAS performances, we consider those of the Axial Interface Device, The Passive Axial Support and the Hydraulic whiffle tree, to obtain the complete axial supporting system performance.

These performances characterise the capability of the system to correct the optical shape of the M1 mirror, particularly the first optical mode : astigmatism and spherical aberration.

the tests performed in Europe and Chile, with the Cell at zenithal position and inclined position, demonstrate the compliance of the system design, in term of :
- AAS and PAS unitary performances
- hydraulic design (piping topology and diameter)

The validation test consist in force measurements performed at the back side of the M1 mirror, with the help of the three specific Axial Interface Device equipped with a load cell
These measurement are dynamic , to record the step response behaviour, and static to record the accuracy of the force step.

The tests are done by the application of a complete map of 150 active force following astigmatism 2N and 10N at 0° and 45°0, and sperical aberration 2N and 10N pattern of relative force, defined as follow :
$F_{ij} = F \text{ x } \rho_i^2$ for the spherical aberration pattern
$F_{ij} = F \text{ x } \rho_i^2\cos(2\varphi j + \theta)$ for the astigmatism pattern
with : i = 1,2,3,4 correspond to the support ring number
φj = the azimuthal position of supports
Fij = the force applied at the support ij
F = max force = 2N or 10N
θ = 0 degree for the first load case, 45° for the second load case

The axial supporting system performances are :

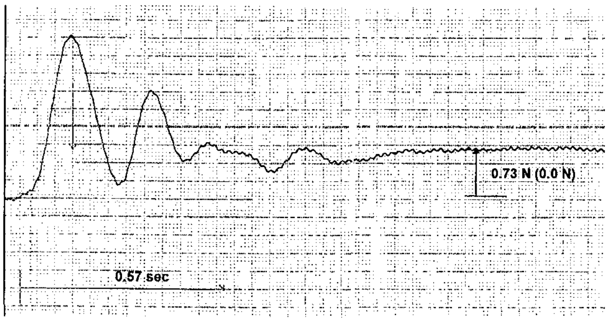
- **Maximum amplitude of set point variation :**	**1300 N (-500N to +800N)**
- **Average force variation speed :**	**> 50 N/s**
- **Absolute force accuracy (AFA):**	**± 2 N**
- **Differential force setting accuracy (DFSA), for 10 N step :**	**± 0.1 N**
- **Settling time for 2N and 10N active force steps (accuracy = 0.1N)**	**lower than 1 sec**
- **Stability**	**better than 0,1 N over 1 minute**

SFIM Industries has performed acceptance tests in Europe and Chile, with the several Instrumented AID and with force pattern applied by the LCU.

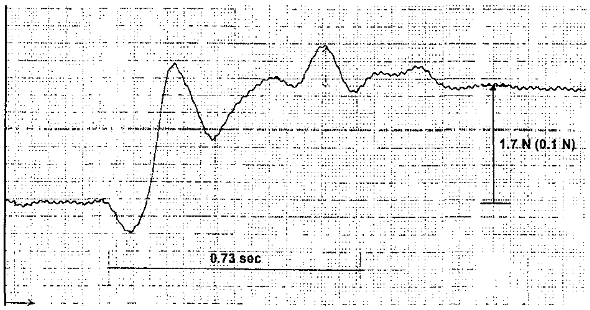
The recording issue from the AID load cell confirm the compliance with the performances, particularly the Differential Force Setting Accuracy, the settling time, the stability and the speed performances.

Additional tests performed with various astigmatism maps give complementary results to be used in preparation of the operational phase of the VLT.

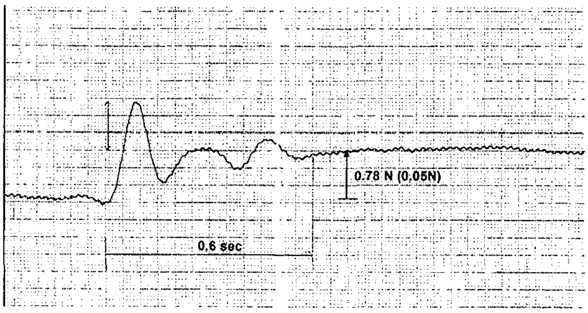
The following test records show the step responses at mirror level, when Fmax=2N map of Astigmatism 0° and 45° and Spherical Aberration is applied : the settling time, the force measured (final state) and the accuracy with respect to the force commanded (under bracket) is indicated.



Astigmatism 0°



Astigmatism 45°



Spherical Aberration

5. REFERENCE

1. S. Stanghellini, « Technical Specification of the M1 Cell - M3 Tower » ; VLT-SPE-ESO-11120-0001 (1995)
2. S. Stanghellini, T. Hovsepian, Ph Legrand « design and construction of the VLT primary mirror cell » ; SPIE proceeding 1996 Landskrona Symposium
3. T. Hovsepian, « Six sector Whiffle tree design report » ; VLT-TRE-GIA-11120-0261 (1996)
4. M. Planard, T. Hovsepian, « VLT M1/M3, Hydraulic subsystem technical Spec. » ; VLT-SPE-GIA-11120-0010 (1996)
5. M. Planard, T. Hovsepian, « Active Axial Support » technical Specification » ; VLT-SPE-GIA-11120-0060 (1995)
6. JM Michelin, « Mirror Position Loop Functional Specification » ; VLT-SPE-GIA-11120-0150 (1997)