VISTA Telescope Mount – Factory testing prior to optics integration

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ABSTRACT

VISTA[1] is a survey telescope which will deliver 0.5 arc second images over a 2 degree diameter unvignetted field of view. The Telescope Work Package which includes both the Mount and M1 support system is being designed and built by VertexRSI. The Contract includes an extensive factory test programme after full assembly of the telescope systems. The main optical elements in projects this size are ordered early so that they are ready for integration with the telescope on site. This means that testing of the telescope with it's optics in the factory environment is rarely possible. So to try and avoid problems during site integration, the scope and extent of hardware and control system factory testing is significant and should be suitably in-depth. This paper describes the metrology and testing carried out to date in the factory environment. In addition the axis control system was simulated using Matlab-Simulink models. The models were also used as the basis of software verification using hardware-in-the-loop tests in a model-based development process. This development process and subsequent factory testing is described in some detail, and covers the mount axes and the M1 support system. In conclusion this paper discusses the perceived usefulness of the extent of the factory testing employed and how this is expected to mesh with the process of telescope and optics integration on site.

Keywords: VISTA, Telescope, Factory, Testing, Mount, Deflection, Simulation, Control, Mirror, Support.

1. INTRODUCTION

VISTA is a survey telescope to be installed at the ESO Cerro Paranal Observatory in Northern Chile. VISTA is a 4-metre class telescope with an "Alt-Az" mount and a Cassegrain instrument rotator. The f/1 primary mirror which is a key to the system design enables the telescope tube to be squat and also necessarily stiff.

Generally speaking in other projects of this size the M1 cell and support system are not contracted with the telescope mount as they are seen as being too diverse in nature and require a different blend of engineering skills and experience. However on VISTA after long discussions with VRSI, both the M1 support system and the mount were included in the one contract. The significant advantage of this contractual arrangement was that the whole telescope mechanical structure was being assembled by the one contractor. This meant that any testing or verification activity had additional validity in that the variables between the test set up and the actual were limited to difference between the optical / Instrument payload simulators used in the testing and the real elements. The most significant advantage of this was that there are no structural variations or differences between the test and the operational configuration.

The telescope Work package contract was placed in Jan 2003 and factory testing was successfully completed in Feb 2006 on the fully assembled telescope in the VRSI facilities in Wortham, Texas. The paper describes certain aspects of the Factory testing that has been carried out, the derivation of these test requirements from performance issues within the system design and the use and usefulness of these results as we commence the site installation and integration of the telescope work package with the other telescope systems. Figure 1 is of the telescope fully assembled in the factory at the time of testing.

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Figure 1: The fully assembled telescope is shown here in the factory. Dummy payloads are visible for the M2 Collimation unit, the M1 and also the Instrument.

2. SYSTEM DESIGN, REQUIREMENTS AND SPECIFICATION OF TESTING

There are a number of different interlinked aspects of the VISTA system design that have driven the way in which the telescope has been specified, designed and tested. The three main aspects that are being considered here are the telescope tube stiffness / repeatability, the M1 support system and the system control.

2.1 Tube Stiffness

The optical design of the VISTA telescope which renders the squat tube structure is by its very nature highly susceptible to image quality degradation due to misalignment of the optics. Some of the causes of this misalignment could be structural deformation, wind excitation or thermal distortion. The main active optical component in the VISTA system with respect to alignment is the M2 which is mounted onto a 5-axis hexapod. No fast tip tilt facility was incorporated at M2. With this system design it was essential to have a stiff tube structure and M1 support system that was:

- Capable of rejecting wind excitation that occurs at a higher frequency (but with lower energy) than the active optics update rate.
- Minimises the static deflections of M1 relative to the cassegrain instrument as these deformations can only be partially corrected for by the active M2.
- Minimise the static deflections between M1 and M2 to preserve range and operate about mid-range on the M2 Unit.
- Minimise the non-repeatable deformations in the structure and subsequently in the alignment of the M1, M2 and instrument.

These system requirements lead to a tight requirement on the stiffness and repeatability of the telescope structure. As the contract included the design of the whole telescope tube it was possible to specify requirements with respect to the optical elements and the cassegrain rotator. The optics and other non contract items in the deflection path were assumed to have representative mass and centre of gravity but not to contribute any stiffness across interfaces to the telescope tube or M1 cell structure, while providing pure translation. This assumption endeavored to separate the dependency of the tube deflection on the payload items e.g. the stiffness of the M2 support structure enhanced by the base plate of the M2 Unit. The figures contained in Table 1 were the predicted performance of the structure from the Finite Element Analysis of the final design and became the baseline against which the testing was conducted.

Table 1: Tube Deflections Requirements

Relative Displacements (88 to 20 deg altitude angle)		Repeatable	Non-repeatable
M1 to Cass	Focus	86 µm	20 µm
	De-centre	48 µm	20 µm
	Tilt	22 µrad	10 µrad
M1 to M2	Focus	18 µm	10 µm
	De-centre	375 µm	20 µm
	Tilt	101 µrad	10 µrad

The testing of these parameters was a clear and stated requirement in the contract from the start and as has been mentioned it was considered fundamental to the performance of the telescope.

2.2 M1 support system

The M1 support system, which consists of 24 lateral supports, 3 lateral definers, 81 active axial supports and 3 axial definers, was laid out in conjunction with the optical design. As such the support system was specified at both the component and system level with regard to performance, architecture and to a lesser degree manner of implementation. The support system testing was required at both the component level and at the system level.

In addition to the component performance the position and attitude of the mounted components was also a tightly specified requirement in order to minimise figure errors due to support alignment. The metrology of the actuators was a specified requirement at the out set of the project. The final phase of testing specified was that of the full up M1 system testing with the M1 Dummy and for this phase it was agreed that the testing would be conducted jointly between the VISTA project office and VRSI. During this phase of testing the open and closed loop balancing of the M1 dummy would be tested. This was a combination of the M1 balancing algorithm running on the M1 Local Control Unit (LCU) driving the VRSI M1 support control electronics and support components.

2.3 System Control

A number of simulations were created using Matlab-Simulink as part of the VISTA controls system development process. They included models of the telescope axes and the M1 control system. The models were also used as the basis of software verification using hardware-in-the-loop tests in a model-based development process.

The telescope axis control development was unusual in that the hardware and the software were essentially off-the-shelf items developed by two different suppliers, VertexRSI and ESO respectively. The hardware was modified by the vendor to suit a UKATC technical specification, and that specification was designed to produce something at least functionally similar to the VLT telescope that ESO produced. However, as the software had been designed in a modular and flexible form that allowed considerable variety in the controlled hardware, the solution became feasible.

Axis control development became a case of obtaining a faithful model of the axis hardware, including this model in a simulation of the axis electronics and software, and tuning the allowed control parameters (rather than creating the control algorithm from scratch as is normally the case).

Figure 2 shows a typical simulation, showing the software model (yellow blocks), and hardware model (cyan block). The hardware model in this simulation was obtained from a vendor's spring-mass model, in other models the actual measured transfer function between rate demand and rate was used.

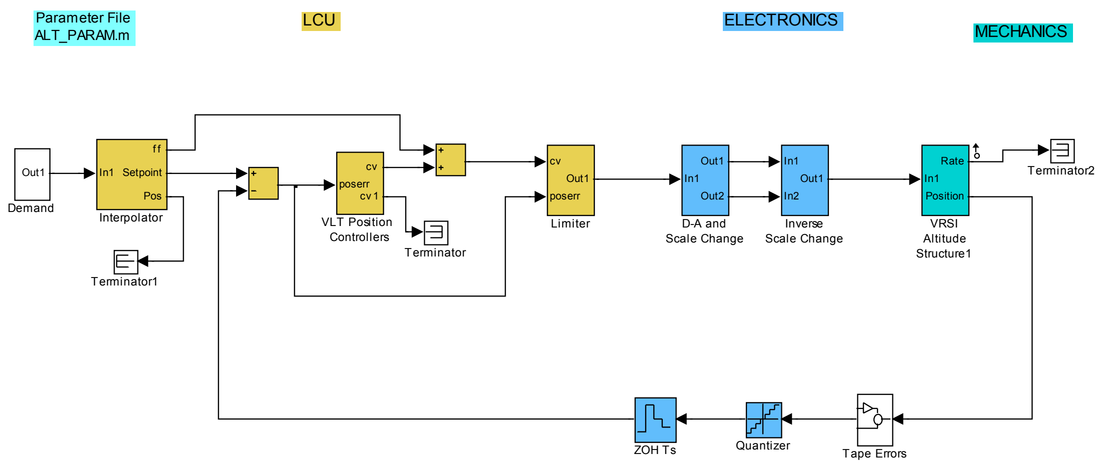

Figure 2 : Typical simulation Model

3. METHOD AND MEANS OF TESTING

3.1 Tube Stiffness

The method for accurately measuring the tube deflections or rather as they were specified the relative deflections of the M1, M2 and Cassegrain Rotator was a complicated process combining a range of different equipment and close co-operation between Vista Project Office (VPO) and VRSI.

The main considerations in the test set up were:

- Metrology equipment accuracy and behaviour when rotated through the gravity field.
- Test fixtures used to provide measurement of deflection at desired points e.g. due to specifying the M1 as a perfectly rigid body and in reality the M1 dummy is not, measuring the deflections from the M1 dummy bore would not be representative – instead a jig was designed (and analysed extensively) to attach to the M1 dummy adjacent to where the M1 definers contact and thus give the rigid body deflections of the M1.
- Process for correctly loading the M1 cell to achieve a load distribution identical to that in operation and used in the analysis.
- Thermal affects during the period of the test.

In order to achieve the levels of accuracy required in measuring de-centre, focus and tilt as specified normally used alignment equipment such as theodolites and micro-alignment telescope were not suitable.
In the end a combination of :

- A linear and angular interferometer from Renishaw configured for high precision machine tool calibration was used for tilt and defocus.
    - Resolution: 0.001 micron, 0.1 micro-radians.
    - Accuracy: cass/m1 ±0.5 micron, ±0.7 micro-radians, cass/m2 ±2.4 micron, ±1.1 micro-radians

- A laser & CCD system from Taylor Hobson was used to measure de-centre (post measurement analysis used to separate out tilt induced component of de-centre).
    - Resolution 0.1 micron.
    - Accuracy ±2.5 micron.

The jigs used are shown in the Figure 3. Figure 4, 5 & 6 are pictures of the jigs from the factory testing:

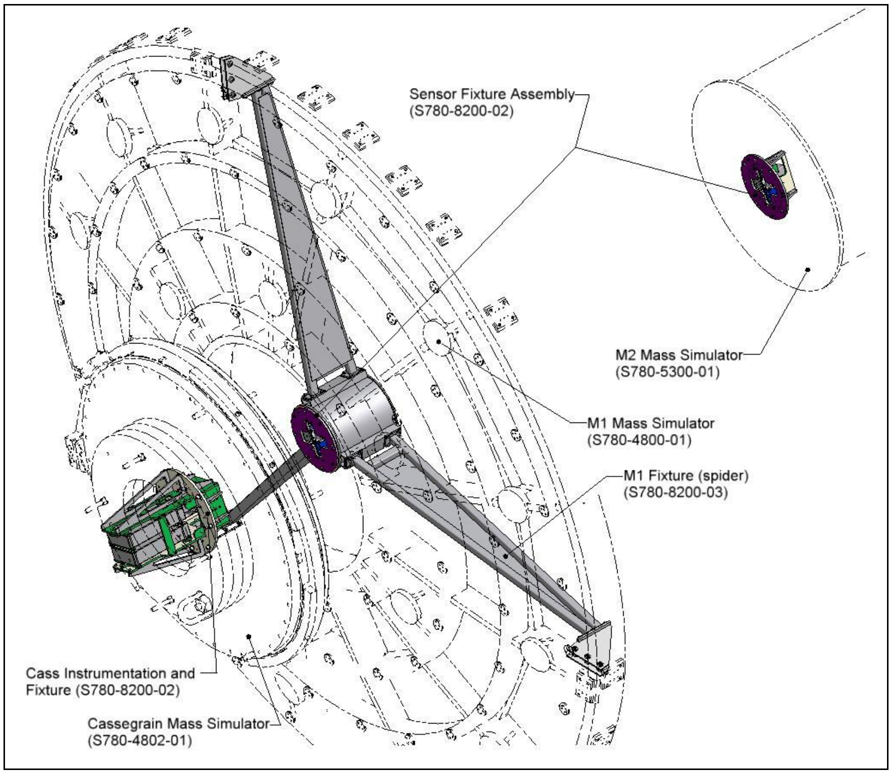

Figure 3: Test fixtures for the M1, M2 and Cassegrain mounting of the test instrumentation.

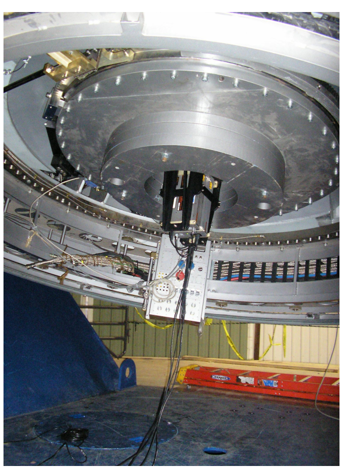

Figure 4: Cassegrain mounting for instrumentation

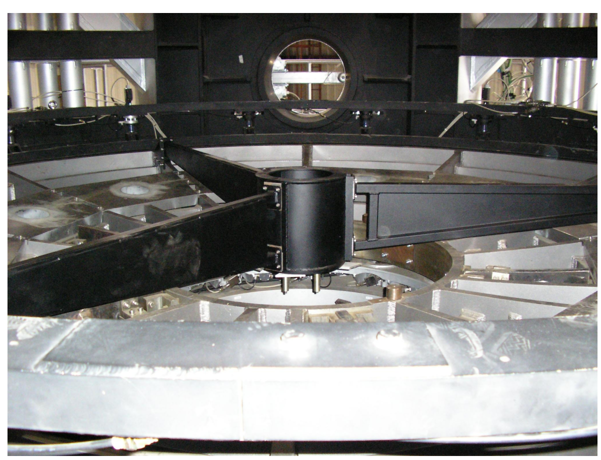

Figure 5 : M1 mounting for instrumentation

Figure 6: M2 system mounting for instrumentation

As the testing was not being carried out in a laboratory environment certain allowances had to be made for the environment in which the testing was carried out and as such an error budget was agreed between VPO and VRSI which formed the allowable limits on the test results with respect to the agreed requirements. An example of the areas considered in the budget are shown in Table 2.

Table 2: Cassegrain to M1 deflection measurements – error budget.

Component	Axial (µm)	Radial (µm)	Tilt (µrad)
Fixture Deflection FEA uncertainty	8.0	0.5	1.5
Accuracy of sensor	0.6	4.2	0.8
Actuator control inaccuracy (VRSI equipment	0.1	0.2	0.1
Thermal distortion of main structure	3.7	5.0	2.4
Thermal distortion of fixtures (not in FEA)	0.9	1.3	0.6
Environmental disturbances	4.0	4.0	3.0
VPO M1 LCU Accuracy	2.0	2.0	1.0
Test equipment mounting hysteresis	4.0	0.2	0.7
Total	23.3	17.4	10.1

In carrying out the test, a significant number of data groups were necessary in order to provide a good characterization of the system. The altitude axis was driven through the complete range and measurements taken at 10 deg intervals. Care was taken to ensure that there was an equal number of data groups for a specific angle that were taken after the tube had reached the desired angle either through ascending or descending. This was specifically carried out to check for the Non-repeatability's in the system.

3.2 M1 support system

The M1 system including the VPO provided LCU was critical to the measurement of the M1 to Cass deflections as the M1 dummy had to be in its balanced configuration during the movements over the altitude range.

The component design was carried out and the factory testing of the prototype definers and actuators was completed in the initial phases of the project before manufacture of the remaining components was started.

The system testing involved testing of the reliable and accurate operation of all the actuators simultaneously. This testing was used to prove both the M1 LCU software as well as the VRSI control electronics and support components. Section

3.3 describes the means and methods used for testing the M1 control system in the labs before the further proving with the actual hardware. Other tests were conducted for example to measure the repeatability of the definer re-seating after the system had been switched off and on,

The metrology of the support system positions was taken using a LECIA laser tracker. The actual position of the contact head of each axial actuator and axial definer was taken using a specially designed jig. The lateral actuators and definers were specified as directional vectors with respect to their attachment point to the M1 and the Tube co-ordinate system. VRSI derived from this and the design of the supports themselves the actual co-ordinate position of the brackets. The positions of the lateral support and definer brackets were measured relative to this and then the measurements were all made relative to the cassegrain rotator datum. – derived positional geometry and jigs for support components

3.3 System Control

Of interest is the method used to verify some of the software operation with the expected hardware. The start-up logic behaviour hardware was modeled in Simulink and this was then converted to a dSpace experiment file. The DSpace system allows a Simulink model to interface with various hardware inputs and outputs in real-time. This enabled safe start-up operation and a number of fault conditions to be tested. The simple Simulink start-up logic model is shown in Figure 7.

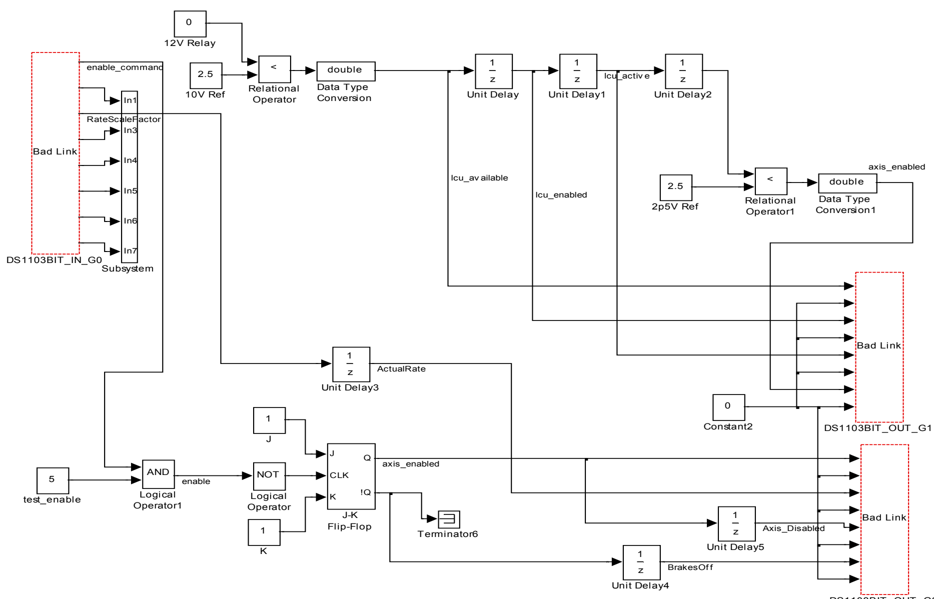

Figure 7 : Simulink start-up Model

In addition, the axis software control loop operation was verified using a small motor-tacho-encoder load (with appropriate scaling in the control parameters), and nearly all of the system fault lines were verified to confirm the mapping between connector pin-outs and software variables.

The small position encoder used was from the same manufacturer (Heidenhain) as the much larger tape encoders on the telescope, and could be used with the same interface card mounted in the UKATC Local Control Units housing the ESO-standard VME hardware.

Using the above processes much of the Axis Control software was able to be exercised and verified before the telescope hardware was ready, performing a useful risk reduction and time saving function

The M1 control software was written in-house (to ESO standards) to suit the M1 control hardware designed by VertexRSI to UKATC specifications.

As both the software and the hardware were new it was important to get as early an indication as possible of any integration problems. To this end, the M1 dynamics were simulated in Simulink and again transferred to dSpace for emulation alongside the software. Figure 8 illustrates the emulation process in block diagram form.

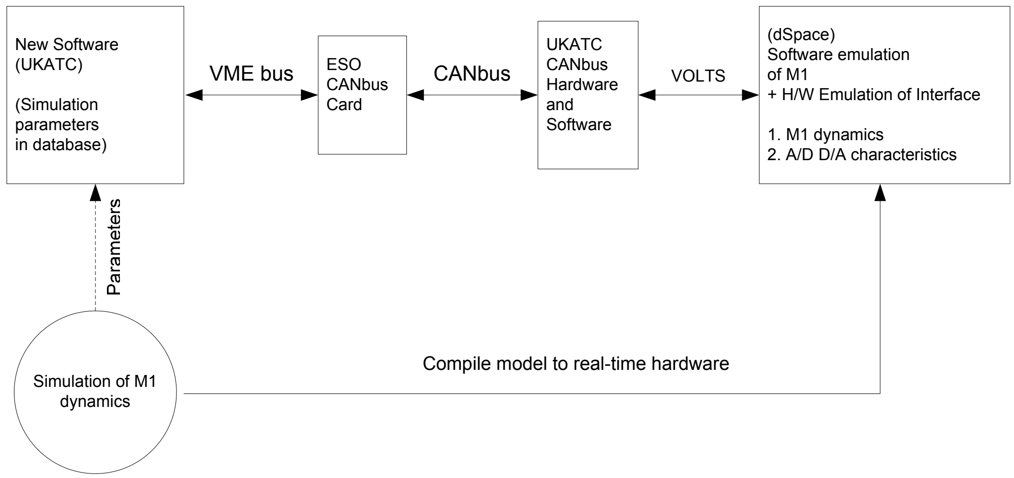

Figure 8 : Emulation Process

Figure 9 shows the simplified simulation for the M1 Lateral dynamics.

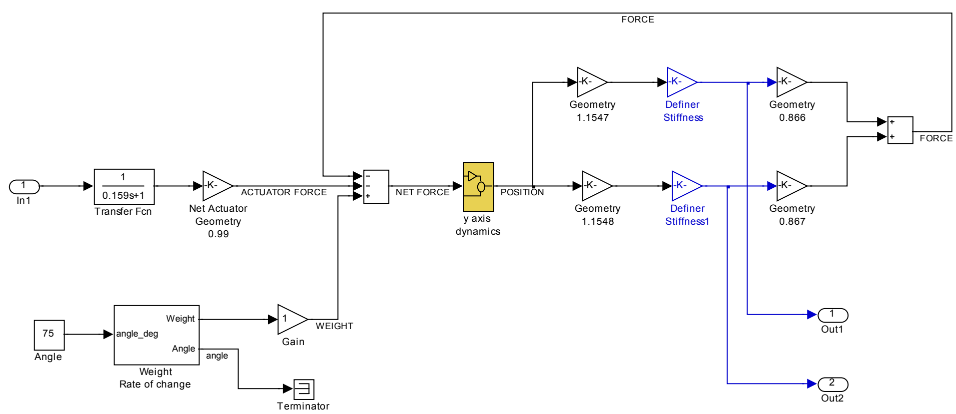

Figure 9 : Simulation for M1 Lateral Dynamics

The translational dynamics are contained within the yellow block, with the definer feedback shown around it.

The corresponding dSpace Lateral control panel is shown in Figure 10. The bar charts show the M1 effective weight, the actuator force and the bipolar definer force, plus the numerical values. The graphical display gave immediate indication of successful or erratic loop behaviour. The M1 angle can be varied in a slew-limited step response fashion (corresponding to Altitude angle changes) and the loop behaviour and settling time measured.

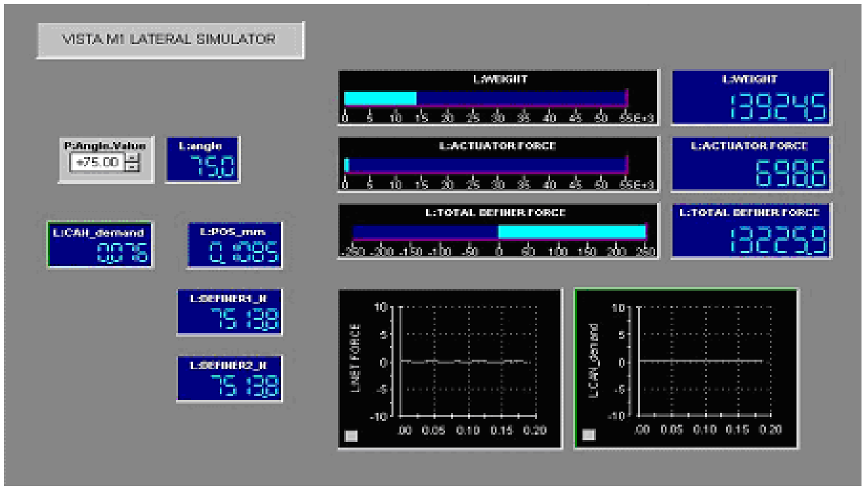

Figure 10 : dSpace Lateral control Panel

4. TEST RESULTS

The majority of the factory testing of the telescope was conducted during November and December of 2005 at the VertexRSI assembly facilities at Wortham Texas. The following reported results and data were taken and analysed over the following weeks to provide the bases of the factory acceptance of the telescope work package.

4.1 Tube Stiffness

In Table 3 the results of the testing are shown with the FEA predicted parameters in brackets. As can be seen in the results the FEA produced figures and the actual test results in some cases were very similar and in other areas show some disparity. It is important when looking at these figures that the test uncertainties identified in the error budgets (Table 2) are not included.

Table 3: Tube Deflections Results

Relative Displacements (88 to 20 deg altitude angle)		Repeatable	Non-repeatable
M1 to Cass	Focus	57.5 µm (86)	7.4 µm (20)
	De-centre	91.0 µm (48)	3.3 µm (20)
	Tilt	20.9 µrad (22)	6.7 µrad (10)
M1 to M2	Focus	199.0 µm (18)	10.8 µm (10)
	De-centre	164.4 µm (375)	14.6 µm (20)
	Tilt	125.9 µrad (101)	9.0 µrad (10)

As an example of both the similarities and the differences, Figure 11 shows the actual results plotted against the predicted performance and as can be seen the M1 to Cass predicted and tested data compare well especially considering that the measurements are in the 10's of microns. This was one of the most important parameters being tested and the agreement between FEA and test was excellent. The results here also involve the supported M1 mirror and as such show that the support system and its control is holding the M1 in its global position within the allowable limits.

However the M1 to M2 measurements show a significant divergence from the FEA results. The form of the test results for the M1 to M2 have the correct shape for the focus deflection change through gravity but are of a higher magnitude. The results in Table 3 show this to be the case for a number of the different parameters i.e. there was relatively good agreement in M1 to cassegrain focus and tilt and M1 to M2 tilt but M1 to cassegrain de-centre and M1 to M2 focus and de-centre show significant differences. There are many possible explanations that could explain the differences such as the test environment, differences in the joint fabrication and the FEA model joint design, FEA model problems etc.

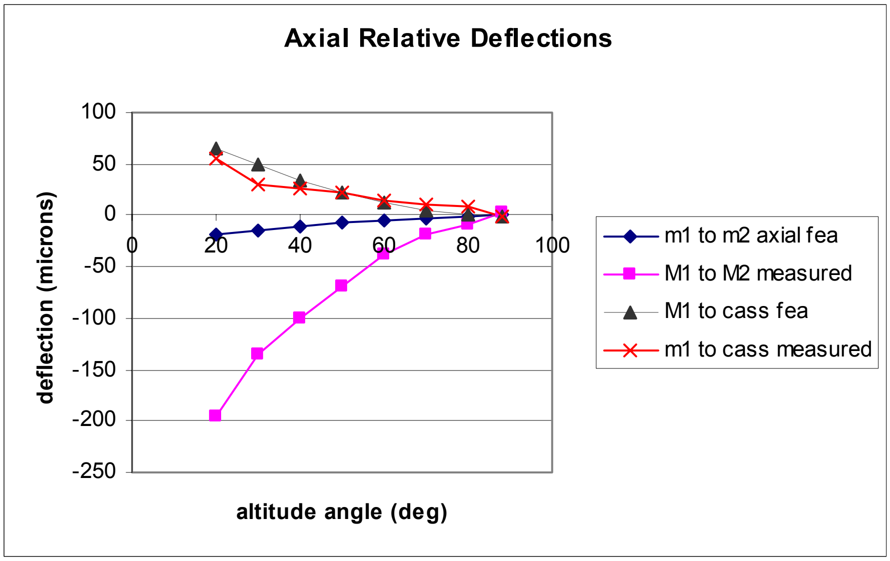

Figure 11 : Axial deflections FEA vs. Test

In order to minimize the thermal effects, the testing was conducted over two early morning runs starting at 4:00am. The instrumentation recorded how the temperature varied over the period of the test and there was a clear indication of the thermal effect on the results that when considered in focus corresponded very closely to the theoretically expected effect. Figure 12 shows this clearly in graph form..

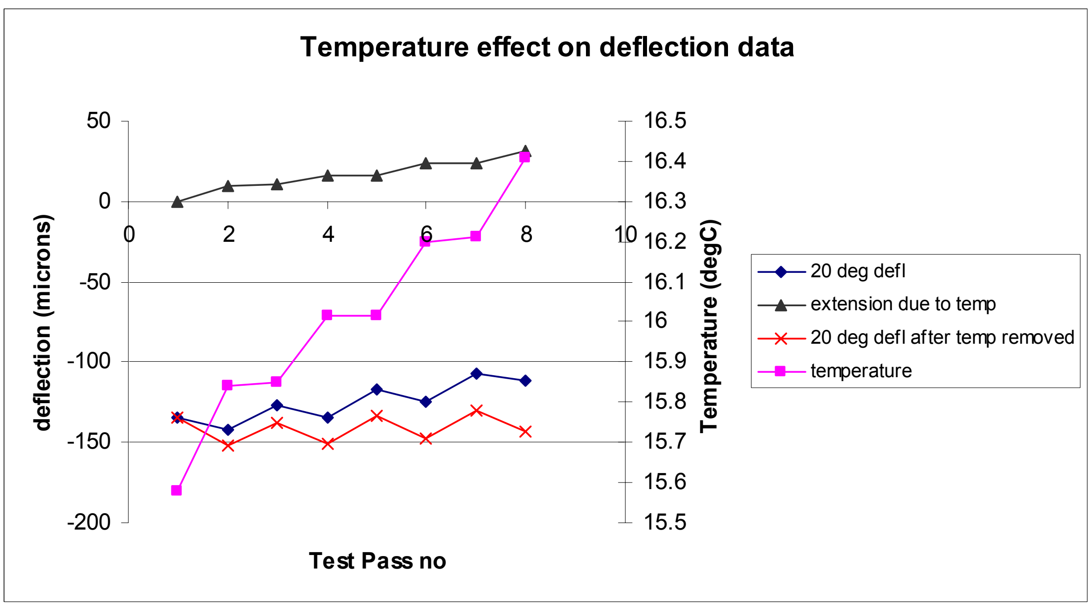

Figure 12: Temperature effect on data results

The most significant set of results which could not be calculated but only estimated based on experience was the non-repeatable components. These estimates are based on experience on different structures and are subject to so many variables in both the design and the fabrication that without testing they are suspect. As can be seen from the results in the Table 3 the non-repeatability measured in the system was extremely low, to the point that they were approaching the accuracy threshold of the test equipment.

The identified thermal drift was removed from the repeatable deflection results to provide the actual repeatable deflections but its effect on the Non-repeatable data was not removed and subsequently if accounted for may cause a further reduction in the Non-repeatable values. However as the non-repeatable values were already well within the allowable this exercise has not been carried out.

The deflection results have been used for both the acceptance of the telescope i.e. to prove that the manufacturing was carried out correctly and that there are no significant issues in assembly of the structure that could lead to misalignments during commissioning. The results also provide a good basis for the 1st approximation of the M2 polynomials for the telescope pointing model relating to deflection. This information may also be useful when it comes to commissioning in that if there are problems of alignment then the separate characteristics and behoviour of the telescope is known.

4.2 M1 system & Control system

The testing of the support system was an integral part of the deflection testing in that it had to be performing within the required limits in order to carry out the test. In addition the system was tested for repeatability of the actuators, the repeatability of the definers when reseating and ability of the system to balance the M1 during slews without feed-forward of angle.
Figure 13 shows the lateral definers load cell feedback during 70deg slews in altitude starting at zenith. The lateral definers were significantly more sensitive to the effects of slewing and also environmental noise than the axial definers. Because of this the time was not taken at this stage to carry out careful tuning of the lateral support loop as the factory environment produced a significant background noise which was effecting the system noticeably.

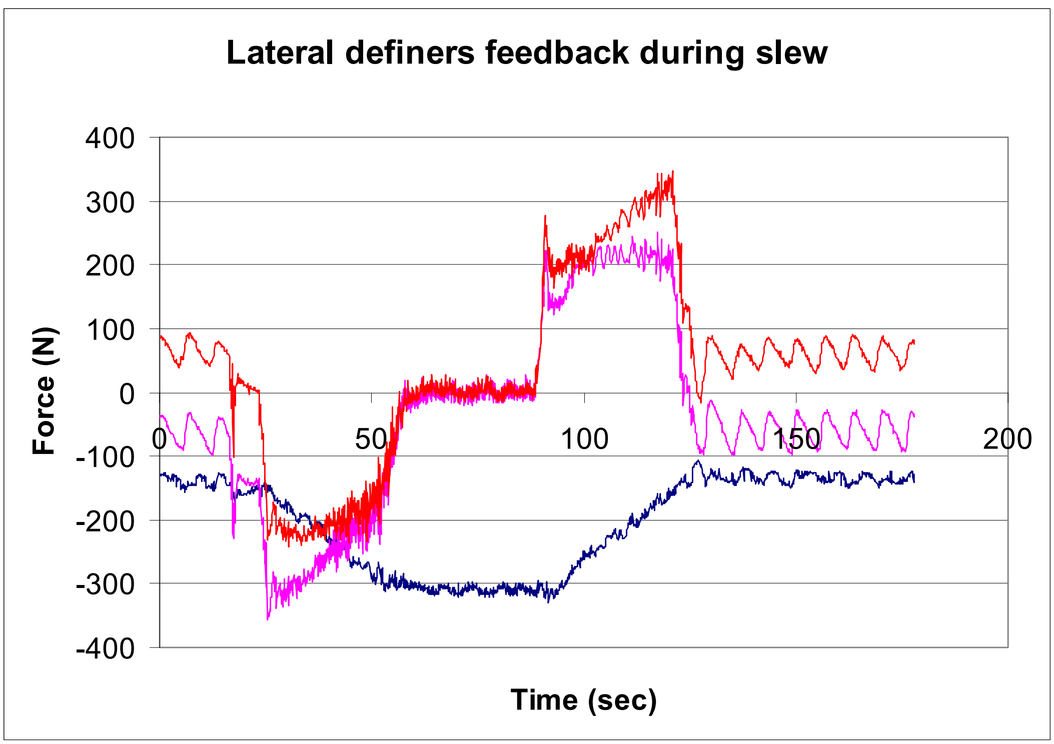

Figure 13 : Lateral Definers Feedback during slewing

As part of the factory testing VPO also undertook integration of the ESO style Local Control Units (LCU) with the VertexRSI control hardware. The pre-testing of the LCU software and start up sequence reduced the time required to get the system operating under LCU control and a number of basic performance tests were carried out duplicating those already carried out by VRSI to check that the system performed under LCU control in the same way and to the same level as under the VRSI control system.

5. CONCLUSIONS

With any complex system, testing of the individual parts is a necessity that cannot be overlooked. If you do not understand how each of those component parts works individually, it is with greater risk that the whole is assembled and commissioned. With the information that has been collected through the factory testing we have a good understanding of how the VISTA Telescope structure performs when subjected to operational loadings. With respect to the deflections in the telescope tube, we already had a good grasp of how the system would behave through the extensive FEA, that understanding has improved and been solidified by the testing carried out. This gives us confidence that as we move into commissioning on site the telescope structure is performing within the allowable limits. If we had not carried out this testing we may have found that the structure performed satisfactorily or we may have discovered problems during commissioning in which case it would have been more complicated after the optics were integrated to determine wherein the problem occurred.

As with most M1 support systems until the whole system is assembled and trialed the actual performance as predicted is not known. With the testing of the M1 support systems as an end to end system integrated to the telescope and still within the factory, integration problems with both the support system and the control were dealt prior to on the mountain commissioning. This end to end system testing again provides the confidence that at the basic level the system works and so the risk of fundamental or major problems on the mountain are reduced significantly.
The same applies to both the lab testing of the axis control system and the integration of the axes LCU's with the telescope hardware in the factory. This has been a common practice of ESO and VPO have found it to also be essential.

The level of testing that VISTA has undertaken in the factory for the telescope Work Package has taken a significant period in the schedule. However the risk reduction for the project with respect to commissioning and ensuring that we are accepting a Telescope structure and support system that perform as we require is deemed to be worth the time taken. In addition the information gathered allows a good start to setting up control parameters and it is hoped that this will then reduce the initial set up time. The fine tuning is yet to be done and without question this is for when the final installation is complete and the telescope is supporting the actual optics and instrument.

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