Analysis of the NOT Primary Mirror Dynamics

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Introduction

On the nights of 12th and 13th May 2000 observations were made using the JOSE camera system, borrowed from the ING, as part of a novel science experiment. This camera was used to image bright objects with a high frame rate and as a consequence has sampled very well all image motion both due to the atmosphere and the telescope. Typical runs acquired images at frequencies in the range 180 - 331 Hz with a spatial resolution of 41mas and with no auto-guiding. Using this data it has been possible to extract the centroid image motion and produce PSFs for several different stars. The spectra show the classical Kolmogarov atmosphere turbulence profile but more importantly superimposed are several lines suggesting oscillations within the telescope itself, the source of these vibrations is the well known primary mirror motion.

Observations

The JOSE camera system consists of an Astromed 4100 controller with a 512x512 frame transfer CCD. The system is controlled from a Sparc10 which has 256 MBytes of memory. This memory is used to store the images in real-time so sets the limit on the maximum length of a single run. The system can read the CCD at a pixel rate of up to 5.5 MHz resulting in a maximum frame rate for a 64x64 window of 331Hz, though with relatively high readout noise. Windows of 64x64, 96x96 and 128x128 pixels where typically used, with the respective frame rates of 331Hz, 259Hz and 182Hz. The camera head, which is peltier cooled, was mounted on the back of the HiRAC filter wheel assembly and all the observations where made using the HiRAC i filter which has a pass band of 750 - 875nm and a through put of about 82%.

The objects observer where ϵ aquilla and γ aquilla on 12th May, at the latter part of the night when the seeing has been estimated, from the co-added frames, to be about 0.4 arc-seconds. The following night α aquilla and α boo where imaged with a seeing of better than 0.6 arc-seconds.

The approximate azimuth and altitude of the telescope for the observations is given in the table 1. The wind direction was typically from the west to north-west, (90 - 150 degrees) at a speed of about 3m/s, so for all the observations the telescope more or less faced into the wind, which would be expected to be the worst direction for wind induced vibrations of the primary mirror.

Information

Previous measurements of telescope oscillations, given in [1] using HiRAC have identified resonant frequencies at 11Hz and 16Hz, though frequencies at these po-

Object	RA	Dec	Azimuth	Altitude	Wind Direction
ϵ aquilla	18 59 37	15 4 6	137	72	100
γ aquilla	19 46 15	10 36 48	157	70	100
α aquilla	19 50 47	8 52 6	110	48	135
α boo	14 15 40	19 10 57	120	73	140

Table 1: Position of telescope for each observation, with the respective wind direction

sitions have been seen in the data they are by no means dominant. One significant different in the two observations, apart from the instrument, was the wind speed. For the HiRAC commissioning it was reported to be 12m/s where as for this run it was typically only 3m/s, during the actual period of data taking.

The resonant frequency of the supported primary mirror is 7.4Hz [2]. This has been calculated assuming the external forces are gravity and the pneumatic support system, and that the stiffness is purely from the load cells. the position of M1 is measured by three load cells and through a closed loop servo the pressures in the bellows is regulated to give nearly zero force on the respective load cell. Each load cell controls the pressure of its 15 corresponding bellows through I/P (current/pressure) converters. To remove any excitation at the resonant frequency of the primary mirror of 7.4Hz by the servo loop the load cells' output amplifier transfer functions where modified, by T. Erm (???), to block this frequency, and as seen from the measured spectra below, the fundamental resonant frequency of the mirror does not appear.

The downward force (in kg) from the mirror is a function of zenith angle (θ_Z) is given as:

$$F_m = M_m.cos(\theta_Z) \tag{1}$$

Where M_m is the mass of the primary mirror (1926kg). Figure 1 shows this graphically.

At zenith and at the zenith angle 80 degrees the loads are 1926kg and 334kg respectively. The support system is designed to maintain a constant pressure on the load cells for all angles, which on the TCS is 750 units, from a full range of 1023 units. Stated in the T. Andersen Memorandum the load cells have an operational range of 5kp (kilopond = 1kg-force), so the maximum load on the cells can therefore not exceed 5 * 750/1023 = 3.66kg (or 36N), or a total load on all three load cells of approximately 11 kg. The actual force is believed to be only of the order of the equivalent of 1kg on each load cell.

The load cells can be considered as a stiff spring with a position sensor, the stiffness of the load cells is given by:

$$K_f = \frac{force}{deflection} = \frac{5kp}{0.035mm} = 142kp/mm \tag{2}$$

Weather Data

Figures 2 and 3 show the wind conditions during the observing nights 12-13 May 2000. It can be seen that the typical wind speed was between 2 - 4 m/s during the period data was taken, the second half of the first night and the whole of the second.

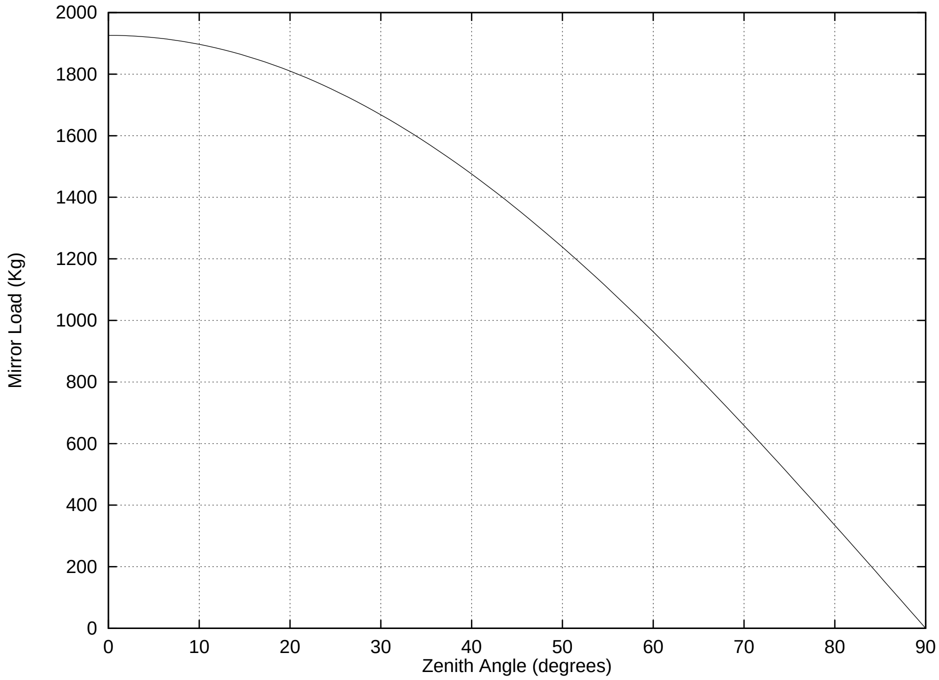

Figure 1: Mirror Load on Bellows verse Zenith Angle

Results

Figure 4 shows the spectra obtained, for the four observations, of the centroid image motion for two orthogonal directions. Some interesting observations that have come out are, that from the same run different frequencies can be observed in the orthogonal axes. For example looking at the two orthogonal spectra from the ϵ aquilla observations clear spikes can be seen in the x-direction at 5.6Hz and 15.1Hz, but in the y-direction the dominant peak is 16Hz with two smaller ones at 10.4Hz and 11.6Hz. This feature is repeated through out the observations with only the occasional frequency appearing in both orthogonal axes at the same time. This suggests the primary mirror is oscillating in high order modes, not just the tip-tilt mode usually suspected. The frequency that appears most often, though not always, is 15.1Hz.

Due to the relative large pixel scale that reduces the image Strehl ratio (ratio of light at the centre of the image to the wings), the individual images where re-samples using sinc interpolation and images of sufficiently high Strehl where shifted and summed together [R. Tubbs, Cambridge]. The resulting image Strehl is less than theoretically predicted, and seems to be caused by about 20% of the light been scattered. The source of this scatter is unknown but a significant contribution is probably from the motion of M1. Other source could be internal scattering in the camera by the entrance window and actual scatter by the telescope mirrors due to dust and scratches. Also the exact figure of the primary mirror is unknown, so can't be corrected for and this can similarly contribute to the reduction in the measured Strehl. The Strehl measured on ϵ aquilla was just over 0.3 where 0.37 was expected for the given seeing conditions.

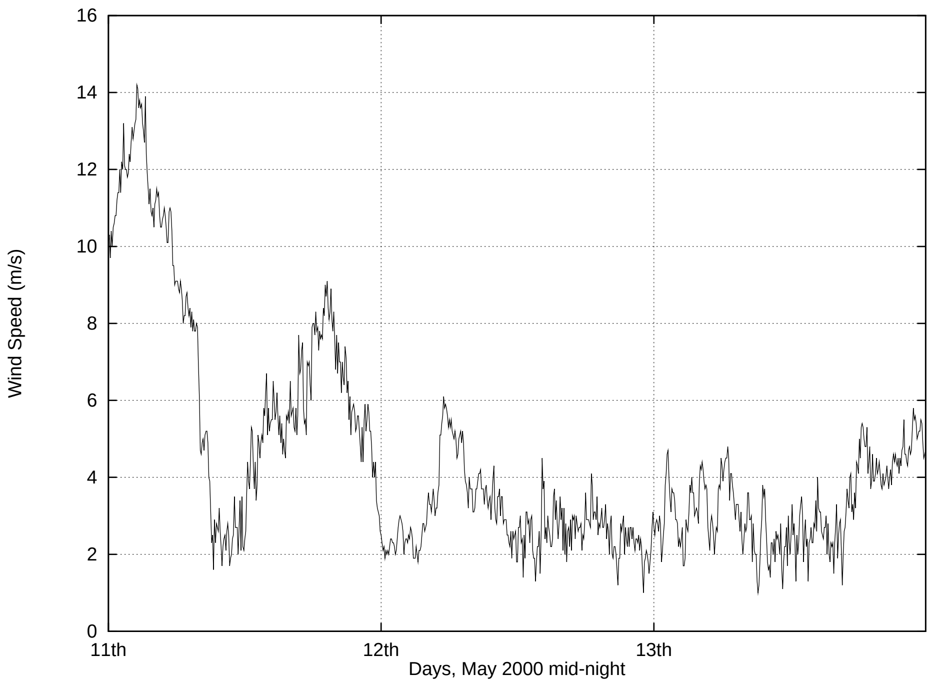

Figure 2: Wind Speed during the two observing nights

Table (2) is a list of frequencies found from the derived centroid motion. The frequencies denoted with a * are very clear, broad, strong features. It can be seen from the table (2) that there are a number of different frequencies including groups around 11Hz and 15Hz, this is in close agreement with the observations made with HiRAC in [1] and the study reported in [3].

Sources of Excitation

There are four possible sources of excitation to the primary mirror, they are the tracking motion of the telescope, the service loft cooling fans, the pneumatic mirror support system and the wind.

The telescope tracking would be expected to contribute virtually nothing the mirror oscillations since the speed of change is slow, the only force on the mirror will be gravity and the compensating bellow force. The gravity vector changes very slowly so would not de expected to induce high frequency oscillations into the telescope.

The service loft cooling fans run continuously and do put significant vibrations into the observing floor, even though the telescope and building are on separate mounts it is known that vibrations can still be transmitted from the building to the telescope mirror. One thing to note, due to a problem with one of the service loft fan units they were turned off for the second half of the night 13 May. In an attempt to try and identify the frequencies produced by the loft fans an accurate accelerometer has be used to measure mechanical vibrations at various positions around the telescope. The output of the accelerometer was connected to a storage oscilloscope and the frequencies interpreted from the trace. The measured frequencies can be seen in table 3.

There is one additional source of oscillation that has not been mentioned and that is from the auto-guider. Errors due to guiding do not appear in this analysis since it was not used for the observations, though in both [1, 3] when guiding was turned on significant low frequency motion was observed in the range 0.1 - 1Hz. Changes have been made to the auto-guider servo loop since the measurements in

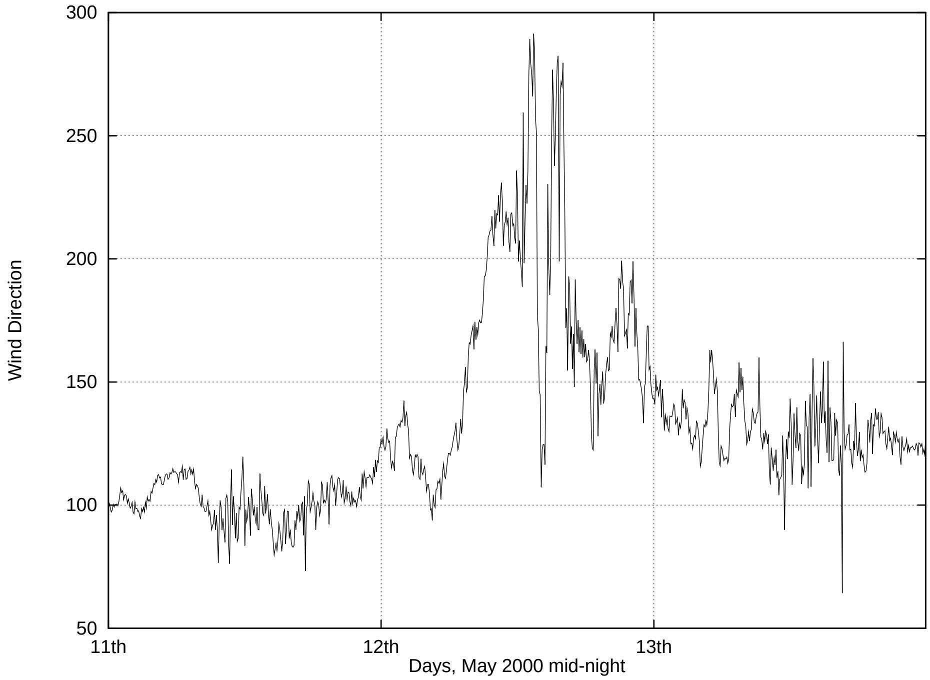

Figure 3: Wind Direction during the two observing nights

[1, 3] so this problem may have now been solved. This needs verifying.

The third force that can excite the primary mirror into oscillation is the support system itself. This is because the pressure to the bellows is up-dated every 100Hz by the TCS, even though they could never respond at such speeds. This control frequency could then be passed into the mirror.

Finally, probably the largest source of excitation to M1 is the wind. Because of the open structure wind hits the mirror from all direction though when looking into the wind the greatest influence would be expected because it would be pushing against the largest surface. During the two nights data was taken the wind speed was relatively constant at about 3m/s and from the same nominal direction. During the HiRAC run in 1996 the wind was up to 12 m/s when very large oscillations where recorded.

Possible Additional Experiments

There are more experiments that could be done to try and identify better the amount of contribution the various sources of vibration make. Listed above are the probable main contributors to the oscillation excitation, telescope motion, the loft fans, the bellow up-date rate and the wind. To measure the influence of these the JOSE camera system (or its replacement) again should be used, but alternatively it has been suggested the load cells could provide the information.

The TCS could record the outputs from the three load cells to identify general M1 motion. This has the attraction, if it works, that nothing needs to be change on the telescope though about half a days work is require to write software to record the load cell values to a file. Before the load cells can be used their frequency response needs to be determined, this can be done by applying a frequency sweep to the bellows at different amplitudes. TCS functions to do this already exist. If it is found that the load cell outputs are useful then tests can then be carried out with the loft fans and the support system control rate to see if they affect the mirror dynamics. Also to measure the influence of the wind, the telescope can be

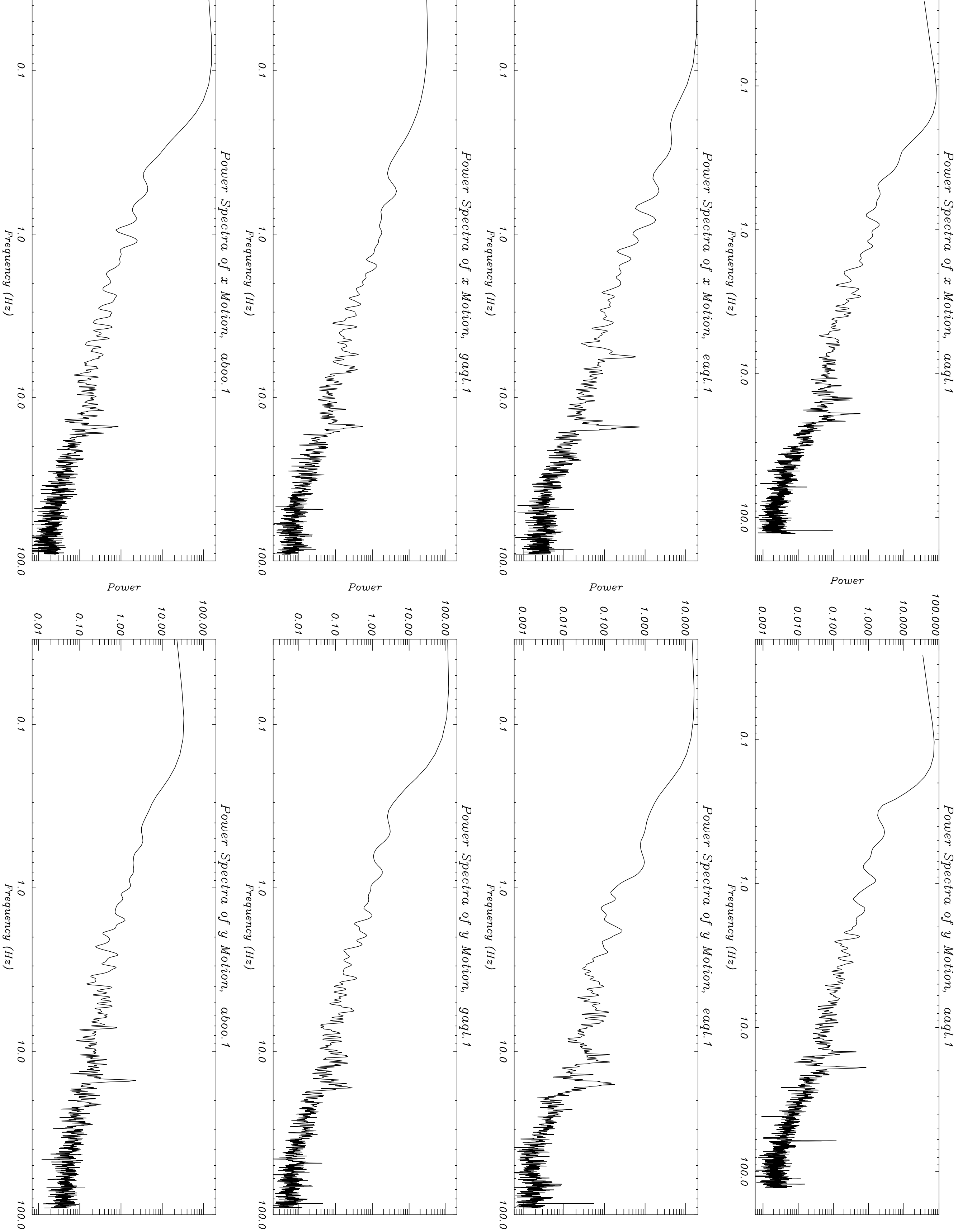

Figure 4: Power Spectra for four different observations

Frequency (Hz)	Object	Direction
5.6*	ϵaql	x
10.7	γaql	y
11.6	ϵaql	y
11.9	γaql	y
14.7*	αaql	x, y
14.9	αaql	x
15.1*	αboo	x, y
15.1*	γaql	x
15.1*	ϵaql	x
16*	ϵaql	y
16.5	αboo	x
16.6	γaql	y
19.1*	αaql	x, y
21.2	αaql	x
47.3	ϵaql	x
61.3	αaql	x, y
68	γaql	x, y
85	ϵaql	x
107	ϵaql	y

Table 2: Frequencies Observed in Spectra

frequency (Hz)	Position
25	Building floor
100	Building floor
50	Telescope floor
200	Telescope floor
300	Telescope floor
50	Telescope, near mirror
500	Telescope, near mirror

Table 3: Mechanical vibrations measured using an accelerometer

positioned in different azimuth directions with-respect-to the wind. All this can be during the day.

The experiments under all the condition described for the load cells can be repeated with the JOSE (or similar) camera, though this need to be at night, obviously. These measurements can be done in conjunction with the actual science programme the original observations where made for.

Solutions

To reduce or remove the mirror oscillations some form of damping system is required. Before T. Erm made an attempt by installing a number of voice-coils around the edge of the mirror but this was found to make things worse. Since it has been found the mirror moves in high order modes, not simply tip-tilt, then a uniformally distributed damping system beneath the mirror is required. Two approaches can be followed, first is to replace the whole pneumatic support system with a new system which uses stiff actuators, though this would be expensive and require significant modifications both to the telescope and the TCS.

An alternative idea for reducing the M1 vibrations is to find some dampers that can be distributed amongst the bellows. As stated above the bellows ensure a constant downwards force onto the load cells for all elevations so it may be possible to just put some suitable spongy type material between the bottom of the mirror and the mirror cell to act as a damper. What ever material is used must not change it properties due to the seasonal temperature differences inside the dome (i.e. not go stiff when cold or soft when warm), and what ever force it exerts on the mirror must be significantly lower than the minimum bellow force otherwise it would distort the mirror surface profile. At the largest useful zenith angle 80^o the downwards force from the mirror is equivalent to 334kg. From above it was stated that the force on the load cells is equivalent to only 3kg so can be ignored. The selected material must not be too stiff as to affect the surface profile but stiff enough to actually absorb the vibrations. The force from any material placed under the mirror will apply a force proportional to its compression, $F = K.d$, where d is the displacement and K the stiffness, so the thickness is important. Also the material should not be hygroscopic.

The above conditions for selection of a suitable damping material to put underneath the mirror suggests it is better to put a large quantity of soft material rather than small stiff localised pieces because, this will distribute the pressure on the back of the mirror more uniformly, and having a small stiffness reduces the thickness criteria. Something of equivalent stiffness to soft sponge, though that does not absorb water, would meet the criteria.

For test purposes pieces of the chosen material can be pushed in between the mirror and the mirror cell, such that they can be removed again. Some thought of the geometry needs to be considered. When the material is in place two tests need to be made, one using a wavefront sensor (e.g. ALFOSC with M. Andersen's analysis software or the built-in one) and the other with the JOSE camera (or load cells). The wavefront sensor is necessary to measure the mirror figure to ensure any material placed under M1 is not distorting it. The JOSE camera is required to see if a reduction in the oscillations has occurred.

Conclusions

It is clear from the results obtain both from this analysis, and from previous ones, the primary mirror of the NOT oscillates and as a consequence degrading the image quality, possibly scattering as much as 20% of the light. It is essential that this vibration be removed to improve the image quality and is extremely desirable before any serious attempt is made to implement passive M1 active optics and necessary if the active optics are to be closed loop. It is understood that future investigations can be made into the actual sources of the primary mirror excitation though from the results already obtained it seems clear that the main source is wind buffering, and therefore some form of damping system is required. Since from the resulting spectra the mirror seems to be oscillating in modes higher than simple tip-tilt, not as a signal monolithic block, then mounting a damping system on the edge would not be sufficient and what is needed is something uniformly distributed beneath the mirror, i.e. next to, or as part of, each bellow. The proposal is to place a soft damping material between the mirror and the mirror cell to act as a damper. This is relatively simple, cheap and reversible.

References

[1] M. Andersen, A. Sorenson. *Commissioning of HiRAC at the Nordic Optical Telescope January 8 - 16, 1996*

[2] T. Andersen *Memorandum 14/7/86*

[3] Michael I. Andersen *Image Motion Measurements At The Nordic Optical Telescope*, 1994