Testing the correction performance of the FTT system

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1 Background

The requirements document INT-403-ENG-0003 sets out the complete set of requirements for the Fast Tip-Tilt (FTT) system and indicates in very general terms how verification of the requirements should take place. This document will concentrate on testing the most challenging performance requirement, namely that for the residual tilt and limiting magnitude. The document will concentrate on Site Acceptance Testing (SAT), but some consideration of factory acceptance (FAT) is also given.

For completeness the relevant requirement is summarised here. The requirement is that, given a set of assumptions about the performance of the telescope and fast tip-tilt actuator (FTTA), the residual two-axis tip-tilt will be less than 0.060 arcsec rms for tip-tilt reference objects brighter than V = 16. These assumptions are:

1. The wavefront error delivered by the UT as specified in Sec. 5 of INT-403-TSP-0002;
2. The photon throughput of the UT as inferred from the coating specifications in Sec. 6 of INT-403-TSP-0002;
3. The response of the UT mount as specified in Sec. 2.6.3 of INT-403-TSP-0003;
4. An FTT actuator that meets the range, resolution and bandwidth specifications in Sec. 4.4 of INT-403-TSP-0003;
5. A bandpass limited in wavelength between 600 nm and 1000 nm reflected towards the tip-tilt sensor;

6. Seeing conditions with Fried parameter $r_0 \geq 14$ cm and turbulent layer wind speeds not exceeding 10 m/s;

7. Observations at the zenith, that is, no effects due to atmospheric dispersion need be considered;

8. That the target has a detected flux at 640 nm, 790 nm, 900 nm and 1000 nm that is lower than in the V band (i.e. at 550 nm) by factors of 0.93, 0.83, 0.78, and 0.74 respectively. These factors correspond to a spectral index of 0.5, which approximates the spectral energy distribution of a typical Type 1 AGN. Note that this distribution is appreciably redder than that of Vega, for which the flux at 790 nm is 0.34 of that at 550nm.

We will call these assumptions the "performance-relevant assumptions", since whether or not these assumptions are fullfilled affects whether or not the FTT performance specifications can be met. The challenge in verifying the performance requirements is that there is no guarantee (in fact, there is relatively little chance) that the performance-relevant assumptions will be met at the time of testing, since for example the seeing will be time-dependent, and the objects being observed will not be at the zenith.

The approach used here is to develop a model of the FTT system which can be used to predict its performance under the range of conditions that can be expected to be encountered, and then measure the performance of the as-built system *together with the conditions prevailing at the time of the test*. If the performance of the system coincides with the model, then this can be used to extrapolate the performance to that which would be expected under the assumed conditions.

The sections below look at how these two sets of measurements, namely the prevailing conditions and the performance of the system can be tested, and then looks at the modelling requirements needed to make the final determination of performance.

2 Measuring the test conditions

The following lists briefly how the conditions relevant to the performance-relevant assumptions can be tested.

Delivered UT wavefront error The UT FAT and SAT results should demonstrate the wavefront quality at a reasonable level of reliability. This can be checked by using the supplied UT WFS if available and using shift-and-add image profiles of stars from the FTT camera to ensure that the image FWHM has not been compromised. A Bhatinov mask inserted in the optical path before the FTT camera can be used to verify that the UT+camera system is focussed correctly.

Photon throughput Measurement of the photon counts received from stars of known brightness and colour can help to verify this. If there are any discrepancies between the measured and expected counts then an independent camera could be used to distinguish between throughput problems in the telescope and those in the FTT system. This independent camera could perhaps be the FLC.

The response of the UT mount The FTT camera should be able to directly verify this by pointing at a star, issuing a step command to the mount and measuring the resulting motion of the image. Careful choice of the step size can minimise the effect of seeing on the measurement.

FTT actuator range, resolution and bandwidth specifications These can be measured by injecting a known tilt signal into the FTTA and measuring the response seen on the FTT camera. The relative timing of the injection of the signal with respect to the readout of the FTT camera needs to be known. See the next section for a method to inject signals in software, but other methods could also be used e.g. having a separate voltage source with a known waveform driving the FTTA. At SAT, the light used for measuring the response will be from a star seen through the atmosphere, so this will introduce noise in the form of the tip/tilt component of the seeing. One way to reject this noise is to inject a narrow-band signal such as a sine wave (or a set of sine waves at discrete frequencies) and to measure the image motion at high sampling rates but over a long period (many seconds). Fourier transforming the response and selecting the Fourier component(s) at the injection frequency/frequencies then makes a set of very narrow-band filters which will have relatively little seeing effect as the seeing is a broad-band noise source. This is a form of "coherent integration", making use of the fact that we know the phase of the injected signal: the alternative is to use "incoherent integration" in the form of a power spectrum, which does not require knowing the phase, but is slightly less efficient and so requires longer integration times to reject the noise.

Bandpass This is not directly relevant to the FTT performance unless it restricts the number of available photons. In this case the photon rate measurements will be sufficient to indicate that there may be a problem here.

Seeing conditions Both the spatial and temporal seeing (as well as the telescope jitter - this is not explicitly mentioned in the requirements but should have been) need to be measured in order to verify the assumptions of the model. The spatial seeing can be determined in a number of ways, and it should be noted that at least one method of spatial seeing determination is required to be delivered as part of the contract. The chief ways of determining the spatial seeing are:

- Using some measure of the "width" (however defined) of the images seen on the FTT camera. Baldwin et al 2008 give a method where the seeing can be determined on a frame-by-frame basis, but it needs to be understood if this method will provide acceptable accuracy on all the objects we would need to measure, since its accuracy will be lower on fainter stars.
- Using a suitable combination of the RMS tip/tilt motion of the FTTA of non-tilt-corrected images and the residual jitter of the images seen on the FTT camera
- Using an external telescope or seeing monitor (but this then does not include any dome seeing).

The temporal seeing is probably best determined using from a temporal power spectrum of the total image motion, derived from a combination of the of the FTTA motion and the residual image motion seen on the FTT camera. This will yield a power spectrum of the combined effects of the telescope jitter and the seeing rather than the spectra of each of these effects individually, but any model for the performance should depend mostly on the combined effects and not the detailed distribution of power between seeing and telescope jitter.

Zenith distance This can be obtained by interogating the telescope control system.

Target colour This can be determined readily from catalogues at the level of accuracy needed here.

3 Measuring the correction performance

Ideally one would measure the absolute level of the residual tilt jitter and compare it to the model, but this depends strongly on the seeing present at the time the measurement is made. A more robust measurement is the fraction of the tilt disturbances at any given frequency which are removed by the servo, as this is more easily predicted by a servo model. Two possible ways to measure the servo disturbance rejection ratio as a function of frequency are:

1. To use the atmosphere as the source of disturbances: here we need to measure the residual image motion with the servo turned off (or with the gain and/or bandwidth turned down) and then with the servo turned on and compare the power spectra of the image motion in the two cases. Measuring the disturbance rejection accurately depends on the assumption that the atmospheric parameters remain stable over the period of the test. This option cannot be used at FAT as there is no source of seeing.

2. To inject a known disturbance into the system. The easiest way to do this is to include a software "port" into which disturbances can be "injected" into the signal going to the FTTA (this simply requires that there is a facility to add a time-dependent offset onto the value sent to the DAC which is "hidden" from the servo software). The disturbances can be either sine waves of known frequency and amplitude, steps of known size, or noise with a known spectrum. The servo software will then try to correct these disturbances and the residual disturbances at the frequencies of interest can be measured using an FFT of the measured image displacements as a function of time. Because we know the phase of the disturbances we can use coherent averaging techniques to measure the phase as well as the amplitude of the response, which can give additional diagnostics of servo performance. To verify that the correct disturbances are indeed being injected, the servo gain and/or bandwidth can be reduced and the image motion at the frequencies of interest measured. At FAT, a separate tip/tilt injection mirror in the optical path from the light source to the camera can be used for disturbance injection, which might be valuable if a mirror with better performance characteristics than the correction mirror is available.

Perhaps the best measurement strategy is to combine both approaches above. In both cases, there is some advantage to using a camera independent of the FTT camera to measure the residual image motion. This may be a relatively small advantage since it is likely that the major uncertainty in measuring the image motion comes from not knowing to sufficient accuracy how "speckle noise" affects the centroid measurement, and so unless the second camera is at a very different wavelength to the first it will suffer from similar and correlated levels of speckle noise. Low-read-noise infrared cameras start at about $20k, and go up to $250k so the extra cost would likely not be worth it unless there is considerable uncertainty about the speckle noise.

These tests would need to be repeated for a variety of test conditions, especially light levels (either by looking at different stars or adding neutral density filters), in order to compare the results with the predictions of the model.

4 Comparing with the model

In order to interpret the data it must be compared to a model of the FTT performance. Thus a model is needed which can take as inputs the relevant test conditions and output relevant diagnostic parameters for comparison with the measured data. The more realistic the model is, the more useful these outputs will be, but this realism comes at a cost in software complexity and run time. At a minimum, each of the test conditions mentioned above needs to be included in the modelling package, at least at the level of providing a facility to determine whether the test conditions experienced include unmodelled effects at a level that would significantly affect the output of the model had they been included in the model. An example of this would be that the effects of the colour of the star might not be included in the model, but in this case the range of acceptable colours and elevations for which the model is acceptably accurate would need to be known.