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Evaluation of the T/T Conditions at Gemini South using NICI AO Telemetry Data

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Abstract. We have used NICI AO telemetry data to evaluate the T/T conditions at Gemini South and how much T/T residuals an instrument such as GPI will be able to achieve. We have found that spatial aliasing in the NICI WFS produces spurious low frequency power that does not allow us to evaluate whether windshake has a strong contribution. We have also found that the NICI data reveal vibrations at high frequency. In the case of GPI, a ~ 2 mas rms vibration line at 279 Hz in the incoming T/T would dominate the GPI residuals. Excessive windshake and high frequency vibrations are two potential effects that could severely restrict the performance of the future ELTs unless specific controllers are implemented.

1 Introduction

Good AO correction requires tip-tilt (T/T) to be corrected to a residual much smaller than the size of the diffraction limited spot. For Extremely Large Telescopes (ELTs), this corresponds to a few milliarcseconds (mas) rms. This level of correction has never been achieved so far. High contrast imagers on 8-meter class telescopes have similar requirements, as they need to keep the star extremely well centered on their coronograph. For example, the Gemini Planet Imager (GPI) requires less than 5 mas rms (tip+tilt), with a goal of 3 mas rms.

T/T can have different sources: atmospheric turbulence; telescope windshake; and vibrations originating from the telescope systems and/or the instruments. T/T errors originating in the atmosphere are, in principle, well characterized by the Kolmogorov theory and the Taylor frozen flow hypothesis. In particular, we can analytically compute their temporal power spectral density (PSD), as a function of the strength and velocity of each turbulence layer [1]. In particular, the theory predicts that at after a cut-off frequency of typically a few Hz, the temporal PSD of atmospheric tilt rapidly drops as a -17/3 power law, making it usually easy to correct with AO. Windshake and vibrations, on the other hand, can have much higher frequency components, making them harder to correct, and are much harder to characterize as they are strongly dependent on the telescope environment.

In this paper, we report on our attempt to use AO telemetry data from NICI, the Gemini South Near-Infrared Coronographic Imager, to evaluate the T/T conditions at Gemini South. In section 2, we present our NICI data and how we processed them to estimate the incoming T/T. We then discuss how the incoming T/T can be broken in two components: the low and the high frequency components. In section 3, we analyze the low frequency component and identify spatial aliasing as a spurious major contributor to this component, which might hide windshake. In section 4, we analyze the high frequency component and evaluate the impact of the vibrations it contains. In section 5, we discuss various possible strategies to mitigate excess low frequency power due e.g. to windshake as well as high frequency vibrations. Finally, section 6 concludes this paper.

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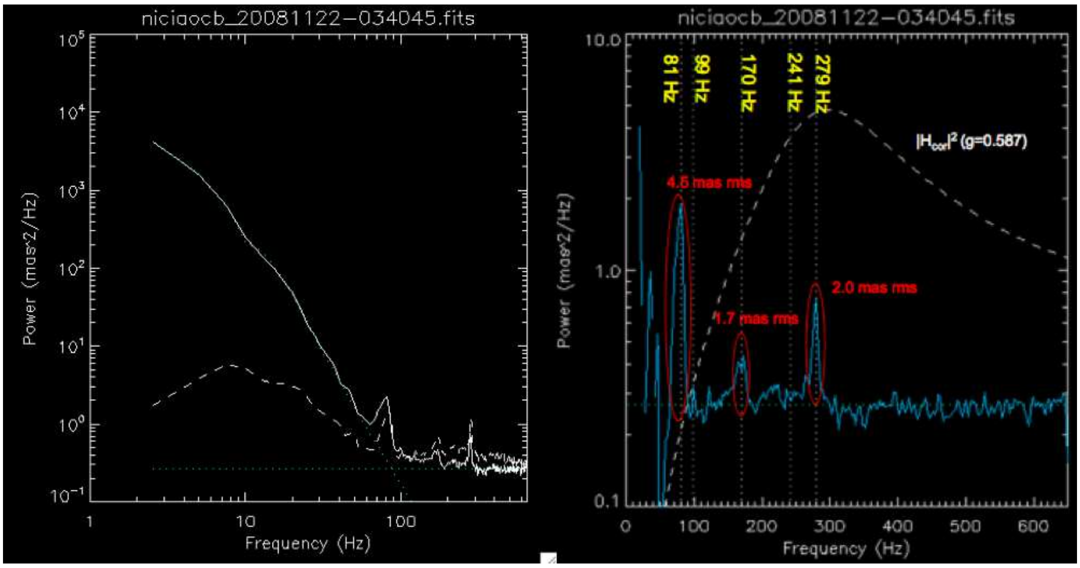

Fig. 1. Left: reconstructed incoming T/T PSD (solid line) from the NICI residual PSD (dashed line) given by the telemetry data. The dotted green lines represent the estimated low frequency component and the estimated noise level. Right: high frequency component (blue line) super-imposed with the GPI rejection transfer function at a frame rate of 2 kHz (dashed line)

2 Reduction of the NICI AO telemetry data

NICI has an 85-element curvature WFS, and the telemtry data are acquired in closed loop, at a frame rate of 1.3 kHz. We obtained 46 telemtry streams (Circular Buffers or CBs), mostly taken in November 2008. The NICI Team provided tools and calibrations to extract tip and tilt from the WFS measurement. They also provided information on the dynamic behaviour of NICI, from which we derived the NICI rejection transfer function. We simply computed the PSD estimate (periodogram) of the tip and tilt coefficients from the telemtry stream and devided by the square modulus of the rejection transfer function to derive an estimate of the open-loop T/T measurement. At this point, the WFS noise contribution should be a flat level, which we estimated using the highest temporal frequencies and subtracted to obtain an estimate of the incoming T/T. Finally, we fitted the inverse of a degree 3 polynomial to estimate the low frequency component of the incoming T/T. For the fit, we only considered frequencies up to 50 Hz, and excluded frequencies than 10 Hz, as they are attenuated by the pre-correction by M2. We then extrapolated this inverse polynomial to frequencies below 10 Hz and above 50 Hz. We considered the result to be the low frequency component, the one that includes atmospheric T/T + windshake. The low frequency component can be subtracted to the estimate of the incoming T/T PSD to obtain the high frequency component, which contains various vibration lines. This whole process is illustrated in figure 1

3 Analysis of the low frequency component

3.1 Residual after GPI correction

The estimated low frequency component can be run through a rejection transfer function to estimate the residuals after AO correction. In the case of GPI, the controller is a simple integrator with an adjustable gain. At a frame rate of $F_s = 2kHz$, the expected latency due to computation is $\tau = 430\mu s$. The rejection transfer function is classicaly approximated by a continuous Laplace function given by $H_{cor}(s) = 1/[1 + H_{ol}(s)]$ where $H_{ol}(s)$ is the open-loop transfer function given by: $H_{ol}(s) = g[1 - \exp(-s/F_s)]/[s/F_s]^2 \exp(-\tau s)$, where g is the loop gain and is set to 0.587, in order to maximize

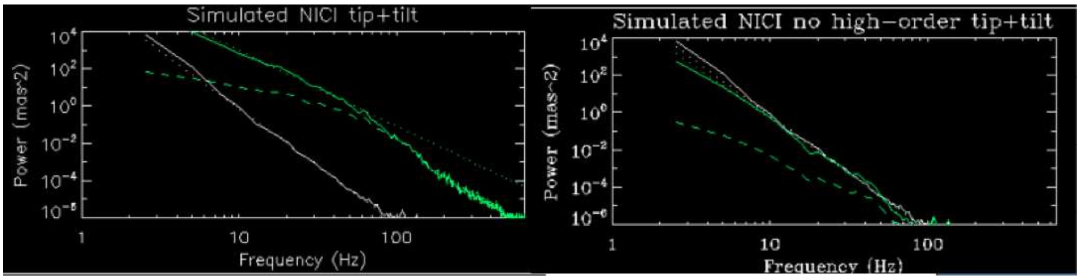

Fig. 2. Simulation results. Solid white curve: T/T PSD in the phase screens. Dotted white curve: -17/3 power law fit. Dahsed green curved: residual T/T PSD obtained from the telemetry stream. Solid green curve: estimated incoming T/T. Dotted green curve: -4 power law fit.

the bandwidth while preserving a 45 degree phase margin (see e.g. [2]). Applying this process, we consistently find residuals well above 10 mas rms. The reason why the residuals are so large is that the PSD of the low frequency component drops off fairly slowly, following approximately a power -3 law. This is much slower than the -17/3 power law drop off predicted by the Kolmogorov theory if the incoming T/T was only due to the atmospheric turbulence. In that case, the residual after GPI correction would be around 1 mas rms.

3.2 The WFS aliasing effect

The much slower drop-off of the T/T PSD compared to what the Kolmogorov theory predicts suggests that there is a strong low frequency component to T/T that does not originate from the atmospheric turbulence. Winshake perhaps. However, further investigations have revealed that this component is simply an artificat of spatial aliasing on the NICI WFS. To show this, we have uses Francois Rigaut's "simul" software to simulate the NICI AO loop. The results are shown in figure 2. We have first verified that the T/T in the phase screens presented to the AO loop indeed follows a -17/3 power law. We then ran the simulation and collected telemetry data. We used the same process as for the real NICI data to obtain an estimate of the incoming T/T PSD. We see on the left graph of figure 2 that the estimated incoming T/T has significantly more power than the real incoming T/T PSD. In particular, we see that up to about 60 Hz, the estimated incoming T/T PSD decreases as a -4 power law.

To prove that this excess power is an artifact of spatial aliasing, we have re-run the same simulation, except that now, the phase screens presented to the AO system are processed such that the high order modes, those that are outside the control range of the NICI defromable mirror, are removed. In that case, no alising should occur. The results are shown on the graph at the right of figure 2. We see that the estimated incoming T/T PSD drops off as a $\sim -17/3$ power law and matches the real incoming T/T PSD very well.

The excess power due to spatial aliasing in the estimated incoming T/T PSD makes a huge difference in the expected residuals. If we take the real T/T PSD (scaled to the nominal GPI $r_0 = 0.145m$) and apply the 2 kHz GPI rejection transfer function, we find a residual of 1.5 mas rms, well below the GPI goal. If instead we use the estimated incoming T/T PSD with the aliasing contribution, the residuals goes up to 9.6 mas rms, well above the GPI requirement.

3.3 Getting rid of the aliasing ?

From the simulations above, it appears that the excess T/T in the NICI data is likely due to spatial aliasing. The T/T data show a -3 power law decrease when our simulation shows a -4 power law decrease, but the real system could well have more aliasing than the simulation predicts, due to misalignment and non-linear effects in the diffrative regime of the curvature WFS.

The simulation results show that if we use the estimated incoming T/T PSD to compute the GPI residuals, about 85of spatial aliasing, which would not affect GPI since GPI has a spatially flitered

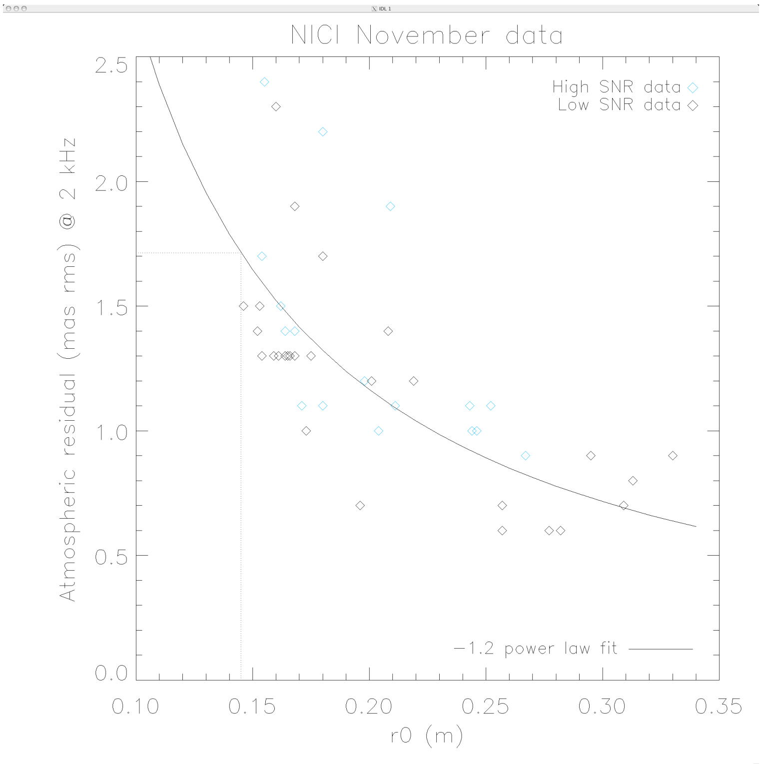

Fig. 3. Estimated T/T residual after GPI correction as a function of r_0 from the NICI data.

WFS. Then, if we assume that all the low frequency component of T/T in NICI is due to the atmospheric turbulence, we could discount the rms of the residuals we find after applying the GPI rejection transfer function to the estimated incoming T/T. This process is shown in figure 3, where we have sorted our NICI telemetry data into high SNR and low SNR catageries, and where the r_0 is estimated from the telemetry data. We expect the atmospheric T/T residuals to be proportional to the atmospheric T/T and therefore to be proportional to $r_0^{-1.2}$. So we fitted a -1.2 power law (to the high SNR data only), and obtained a fairly reasonnable fit. From this fitted curve, we read that at the median GPI $r_0 = 0.145m$, the residual T/T is about 1.7 mas rms, which is below our goal.

This result of a median T/T residual of 1.7 mas rms for GPI was arrived to with a big leap of faith, which is assuming that all the low frequency T/T component is due to atmospheric turbulence, and not windshake. Because T/T from windshake has no high order counterpart, we cannot apply the 85% discount factor. Our calculation would then severely underestimate the windshake contribution. The problem is that the contribution of spatial aliasing is so large that it is hard to determine whether there is windshake or not without external data that we don't have. As a result, 1.7 mas rms median T/T residual is only a lower bound. The upper bound can be obtained by not applying the 85% discount at all. It is 11 mas rms. We know that atmospheric turbulence does have a significant contribution, so it is safe to assume that the reality is closer to the lower bound than to the upper bound, but how close is unclear.

4 Analysis of the high frequency component

The high frequency component of the incoming T/T estimated from the NICI telemetry data (right panel of figure 1) exhibits several vibration peaks. All our data exhibit peaks at 81 Hz, 170 Hz and 279 Hz, with varying intensity. Some data also exhibit lower peaks at 99 Hz and 241 Hz. The strongest peak is always at 81 Hz. However, at 2 kHz, GPI still has a fairly good rejection at this frequency, as shown by the rejection transfer function that is overplotted on figure 1. Although not as high, the peak at 279 Hz would be the most problematic in the case of GPI, because it lies right at the overshoot of the transfer function (the peak would be amplified by a factor 2.16). Across all our NICI data, the 279 Hz peak has a mean amplitude of 2.1 mas rms with a standard deviation of 0.8 rms.The amplification of this peak, combined with the reisdual of the low frequency component discussed in the section above, would give a total mean T/T residual of 4.8 mas rms with a standard deviation of 0.8 mas rms. This would barely satisfy the GPI requirements.

It is surprising and certainly worrying to see significant vibration levels at such high frequencies. However, the fact that the frequencies are so high indicate that it is unlikely that the source of these vibrations are in the telescope. Rather, they likely come from smaller optical elements within NICI, and thus would likely not affect another instrument such as GPI. Also, it is worth noting that, while these vibration would be a problem for GPI or for the ELTs, they are not large enough to significantly affect NICI itself, and have likely been unoticed so far.

5 Possible mitigation strategies

As discussed in section 3, spatial aliasing could hide a fairly strong windshake component in the low frequency component of the incoming T/T. A type-II controller could be used to increase the rejection of this component [2] [6]. More generally, the Kalman framework could be used to tailor the rejection transfer function to optimally reject the incoming T/T (see e.g. [3]). The Kalman framwork can also be used to specifically reject vibrations, which are considered as colored noise [4]. In the case where the vibration affect the WFS path and not the imagery path, the controller can be designed to ignore this vibration rather than try to correct it [7]. Other approaches that we are persuing to mitigate vibrations include using explicit notch filters built into the AO controller and using local pure oscillators whose frequencies and phases are continuously updated by a phase-locked loop [5].

6 Conclusion

Our attempt to use the NICI AO telemetry data to characterize the T/T conditions at Gemini South has been only partially successful. We were able to consistently identify strong vibration lines at frequencies so high (> 100 Hz) that they would be very challenging to correct, unless a specific controller is designed. However, these vibrations are likely to come from NICI itself and may not affect a different instrument. We have found that we were not able to correctly identify the low frequency component of the incoming T/T due to spatial aliasing on the WFS, which makes the T/T PSD appear to decrease much slower than expected. Excess power due to windshake would be swamped by this spurious aliasing component and therefore could not be measured. It is worth noting that further simulations, as well as analysis of AO data from other systems such as Altair on Gemini North, have shown that spatial aliasing affects Shack-Hartmann WFSs just as they do with curvature WFS such as in NICI, making it very problematic to correctly characterize T/T on any telescope.

7 Ackowledgments

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References

1. J.-M. Conan,G. Rousset and P.-Y. Madec, J. Opt. Soc. Am. A **12**, (1997),1559-1570
2. Véran, Jean-Pierre and Herriot, Glen, SPIE Conference Series, **6272**, (2006)

3. L. Poyneer, B. Macintosh and J.-P. Véran, J. Opt. Soc. Am. A **24**, (2007), 2645
4. C. Petit, J. M. Conan, C. Kulcsar, H. F. Raynaud, and T. Fusco, Opt. Exp.**16**, (2008) 87-97
5. N. Di Lieto, P. Haguenauer, J. Sahlmanna, G. Vasishtb, SPIE Conference Series, **7015**, (2008)
6. J.-P. Véran and G. Herriot, in preparation (2009)
7. L. Poyneer and J.-P. Véran, in preparation (2009)