Predicting the future: Predictive control for astronomical adaptive optics

Kooten M.A.M. van

Author: Kooten, M.A.M. van
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Summary

The field of exoplanet research is rapidly advancing through the development of new technology, observing techniques, and post-processing methods. In the last 30 years, thousands of exoplanet candidates have been found through various methods. These discoveries have revealed a zoo of exoplanetary systems looking very different from our own Solar System; orbital period, mass, and radius can all vary greatly from system to system. This dissertation contains two very distinctive parts, both related to the measurement of exoplanetary systems.

The first part of this dissertation, Chapter 2, investigates 8 light curves (flux of a star as a function of time) found in the Kepler data archive. These light curves show periodic brightening events that look different from a normal exoplanet signal (which typically shows a decrease in light intensity). To understand what these signals might be, we investigate two possible mechanisms to explain the observed light curves, namely: forward scattering from an optically thin dust cloud, and tidal interactions from a close binary star system. From modelling and fitting to the data, we find that both of these models can explain the observed data. To truly determine if the signals are due to a binary star system or possibly a dust cloud around a star radial velocity data would be needed.

The second part of this dissertation, Chapters 3 through 6, focuses on high-contrast imaging (HCI) that spatially separates the stellar light from that of the orbiting exoplanet. Current HCI instruments are more sensitive to exoplanets orbiting far out from their host star. To probe the regions close-in to the star, the extreme adaptive optics (XAO) system needs to improve in performance. An XAO system aims to correct for any aberrations of the phase of the incoming light in real-time. However, some residual phase disturbance remains in the corrected signal due, in part, to the continuous evolution of turbulence during the time it takes the XAO to measure the phase and subsequently correct for the aberrations (or the so-called servo-lag). The variance of this residual disturbance needs to be minimised. This servo-lag error typically results in a butterfly pattern near the star in the image plane, preventing HCI from achieving the necessary contrasts to image close-in exoplanets. This dissertation focuses on data-driven predictive control to address the servo-lag error.

We first investigate why current efforts in prediction have not led to the expected gains in performance when comparing simulation results to on-sky tests. We specifically study what effects could be missing from current simulations that might explain the differences. All simulations performed for adaptive optics control do not include any non-stationary behaviour of atmospheric turbulence that is a main source of phase aberrations. In simulations with time-varying turbulence caused by varying wind speed, we demonstrate that an XAO system loses performance. For a standard integral controller, sub-second wind speed fluctuations affect contrast by less than 5%. Wind speed changes on longer timescales, however, lead to a much larger loss

in contrast than theoretically expected. A linear data-driven predictor will also lose performance due to the inability to track the varying statistics compared to its optimal implementation. With the understanding of how prediction performs in simulation under time varying conditions, we apply a linear data-driven predictor to VLT/SPHERE XAO telemetry. We find for the 27 various observing conditions studied, the predictive control XAO correction is more reliable and consistent. The optical turbulence, however, as seen by VLT/SPHERE appears to be time-invariant. We also find that using previous states of the phase at a given point in space as input to the predictor has a larger impact than providing the predictor knowledge about neighbouring measurements.

As HCI systems are being built for the next generation of large telescopes, it is necessary to fully understand the relation between atmospheric turbulence, predictive control, and contrast. To do this, it is imperative to first understand the main differences in the performance of linear prediction at various observatory locations. This requires a good understanding of the telescopes, their instruments and the full implementation of their controllers, as well as the atmosphere above the observatories. At specific sites, different predictive control schemes might be better suited due to the statistical behaviour of atmosphere, telescope vibrations, etc. Since the raw contrast is the critical performance index for HCI, determining whether predictive control can be used to directly optimise the raw contrast is an interesting research direction. Another crucial step for XAO control is to have flexible instruments and telescope facilities to allow for the testing of new control schemes for further development. Being able to test controllers in real-life situations under a variety of conditions is invaluable. By looking into the topics outlined above, the control community can provide the best performance for HCI systems such that the contrast at smaller angular resolutions will allow for the imaging, and subsequent characterisation, for far away and close-in exoplanets.