Satellite and debris characterisation in LEO and GEO using adaptive optics

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ABSTRACT

Ground based optical measurements provide useful information for space situational awareness. We report on the design of an adaptive optics (AO) system built by the Research School of Astronomy and Astrophysics at the Australian National University. The adaptive optics imaging (AOI) system is built for a 1.8 m telescope at Mount Stromlo Observatory in Canberra, Australia. AOI uses a 277 actuator deformable mirror (DM) and Shack Hartmann wavefront sensor operating at up to 2kHz. We have improved imaging quality with custom lenses optimised for a 600 - 950 nm wavelength range. We use an acquisition mode with a 75 arcsecond field of view to assist in locating objects quickly. We have completed the optical and mechanical design of AOI. The system is currently being built and we will integrate it onto the telescope and begin on-sky operating in early 2018.

1 INTRODUCTION

Optical measurements can provide important information for tracking and characterising objects to better understanding their behaviour. Satellites and debris in low Earth orbit (LEO) can be tracked with high accuracy using satellite laser ranging (SLR) and debris laser ranging (DLR) systems. SLR systems can track cooperative targets to millimeter accuracy [1], while DLR can track debris with precision up to 1 m [2, 3].

Beyond LEO laser ranging techniques become ineffective as the return flux becomes too low to measure. Passive tracking can be used for objects further than LEO by capturing images of objects illuminated by the sun. The position is measured by centroiding the object in the captured image and using telescope tracking information to determine the position.

Object position can be measured with high accuracy, however it is difficult to predict where an object will be in the future. This is due to the dynamic forces acting on the body such as; gravitational forces, atmospheric effects and solar radiation pressure. The size, shape and orientation can impact how these parameters affect the orbit [4]. Better understanding of how these parameters impact an object orbit allows for improved orbit predictions to be made which can increase the accuracy of collision predictions. With enough warning of a collision action can be taken to move satellites to avoid a collision and reduce the threat of a Kessler Syndrome [5].

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Ground based observation is made difficult due to the atmosphere distorting images and preventing features being resolved. Much like astronomical applications the effects of the atmosphere can be reduced by using adaptive optics (AO), which will correct the wavefront distortions and allow the full resolution of the telescope to be exploited [6]. Applying AO to satellite imaging has been shown to improve image quality and allow features such as solar panels to be resolved [7]. Rotation of the objects were observed by measuring how the feature location was changing over time.

2 AOI: ADAPTIVE OPTICS IMAGING SYSTEM

We have developed the Adaptive Optics Imaging (AOI) system for capturing images of satellies and debris in low Earth orbit (LEO) and geostationary orbit (GEO). The system will operate on a 1.8 m telescope located at Mt. Stromlo Observatory, Canberra, Australia. AOI will provide AO correction in seeing conditions of 2 arcseconds or better. The atmospheric conditions at Mt. Stromlo have not been conclusively measured, however a campaign is currently under way to make these measurements [8].

We will operate AOI in two scenarios; using a natural guide star (NGS) or laser guide star (LGS) for wavefront measurement. As the object moves quickly across the sky we cannot use a stellar source as our NGS. Instead we use the object being imaged as the NGS to obtain the wavefront measurement for the AO system. To do this we must split the light between the wavefront sensor and imaging camera.

When using the laser guide star we will create an artificial beacon in the sodium layer of the atmosphere to obtain the wavefront measurement. A laser guide star will enable us to image fainter objects as more light can be sent to the imaging camera.

2.1 LEO IMAGING

With the 1.8 m telescope and AOI we will resolve objects 50 cm in size at a range of 800 km and imaging wavelength of 800 nm. This enables us to characterise satellites and debris in LEO by observing the size and shape of the objects. We will be able to resolve specific features such as solar panels or the satellite body. By resolving features of the object we can obtain a better measurement of the centroid, which will aid in improving orbital predictions as we can understand how rotation and external forces may act upon the object.

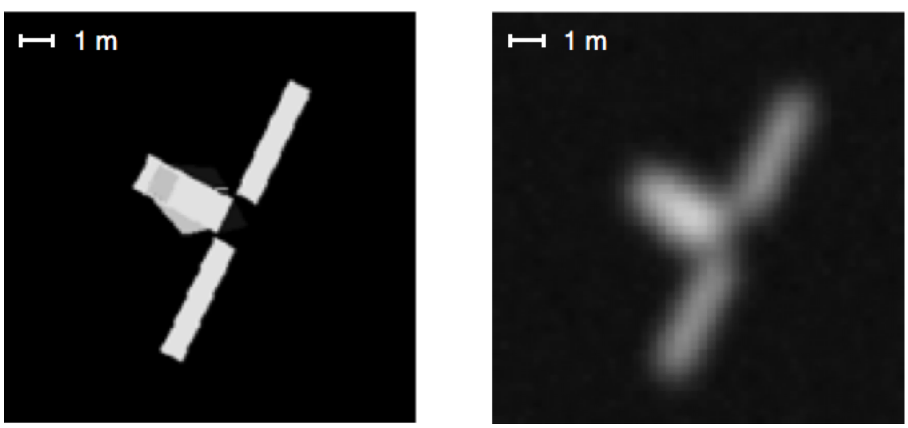

Fig. 1: Left: Ideal image of an iridium satellite. Right: Simulated image of satellite through AOI. The image is an 50 $\times$ 50 pixel area of the detector.

Fig. 1 shows a simulation of an iridium satellite as seen through the AO system optics. The left image shows the truth image of the satellite and the right the image obtained by the AO system through the telescope. The size and shape of the satellite body is visible and the two solar panels can be resolved. A resolved image such as Fig. 1 would allow for rotation measurement as the change in solar panel and body position could be measured over time.

2.2 GEO TRACKING

We will use AOI to obtain high accuracy position measurements of satellites in GEO. We will use stars from the Gaia catalogue as an astrometric reference to measure the position of a satellite as is passes by the star. The concept of operation for tracking in GEO is shown in Fig. 2. We will follow the reference star with the telescope and when the satellite is within 15 arcseconds we will capture images. We will use centroiding to obtain the position of the satellite as it passes by the reference star to determine its position.

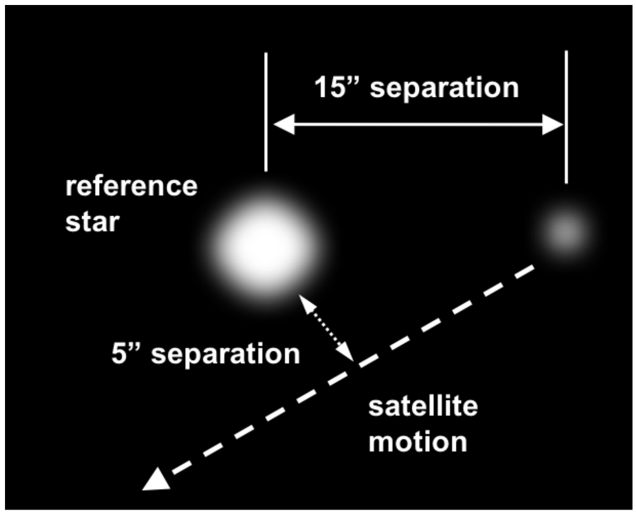

Fig. 2: GEO imaging operational concept. The satellite will be imaged while it is within 15 arcseconds of the reference star. The satellite passes within 5 acrseconds of the reference star during the imaging period.

With AOI we can track smaller and fainter objects than a system without AO. The AO system reduces the speckle in our image and concentrates light onto a fewer pixels allowing fainter objects to be detected. AOI will allow us to track objects of magnitude 15 or brighter, which is equivalent to objects of 1 m^2 or larger in size. We will obtain positional measurements with accuracy of approximately 1 m.

3 OPTICAL DESIGN

We have finalised the optical design of the AO system, with the layout shown in Fig. 3. Light for the telescope is collimated and travels along a 20 m Coudé path to a clean room containing AOI. The parabolic mirror focusses the beam and it is collimated by two lenses to 24 mm diameter, the deformable mirror (DM) aperture size. After reflecting off the DM the beam passed through a dichroic beamsplitter where wavelengths between 450 and 800 nm are transmitted to the wavefront sensor and wavelengths 800 to 950 nm are reflected to the imaging camera.

We selected a 277 actuator DM and Shack Hartmann wavefront sensor operating at 2 kHz. We found that these specifications gave the best AO performance in the design conditions of 2 arcsecond seeing or better [9].

Images are captured with a Nuvu Hnu 512 EMCCD camera. This camera has 512 $\times$ 512 pixels and will operate at speeds of up to 60 Hz. We will operate the camera at $>$30 Hz to reduce the effects of tip-tilt and object rotations. We will also employ lucky imaging techniques to shift and stack to best quality images to improve the final imaging quality.

Imaging performance of the system was improved by using a compound imaging lens consisting of two custom design lenses. We designed these lenses to reduce optical aberrations over a wavelength range of 600 to 950 nm. The custom lenses allow us to achieve diffraction limited imaging over the 22 arcsecond field of view of the system. The spot diagrams produced over wavelengths 800 - 950 nm are shown in Fig. 4.

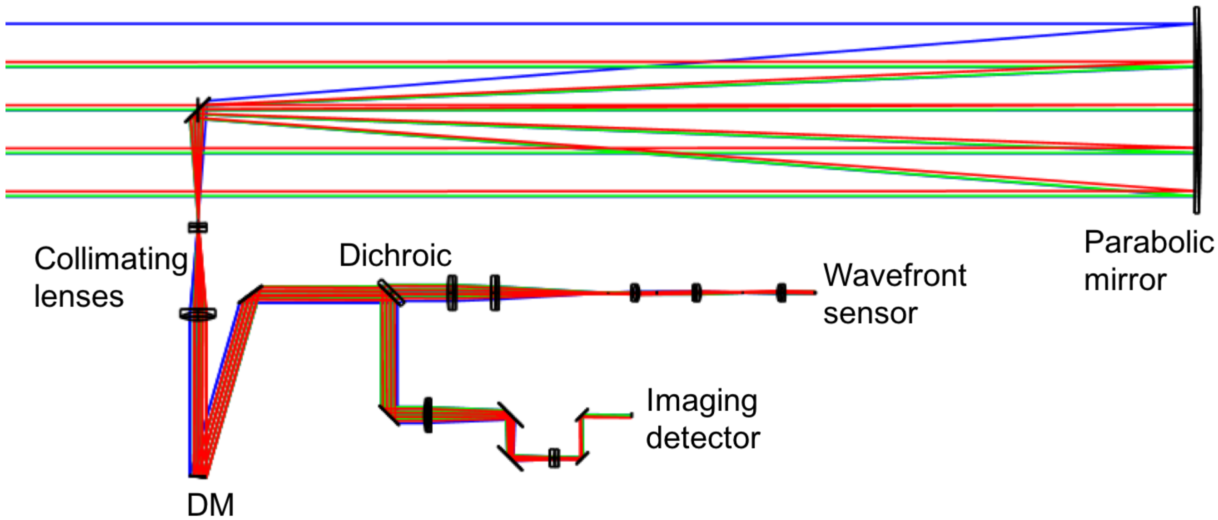

Fig. 3: Layout of the AOI system. The parabolic mirror focusses the beam which is collimated to the DM pupil size by two lenses. After reflecting off the DM light is split by the dichroic between the wavefront sensor and imaging arm.

We have implemented a system where the second imaging lens can be removed to increase the field of view of the system to 75 arcseconds. This mode can be enabled and disabled quickly to assist in locating objects. The acquisition mode of the system provides an on-sky area which is 9 times larger than the standard imaging mode, which increases the likelihood of finding the object in the short duration it will be in view of the telescope.

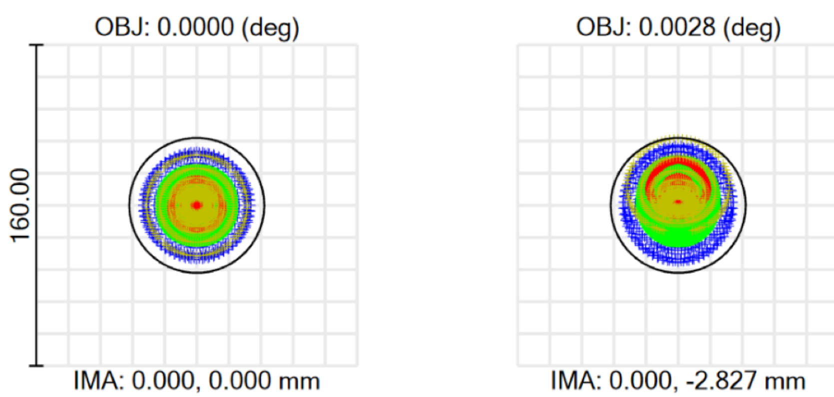

Fig. 4: Spot diagram produced at imaging camera over wavelength range 800 - 950 nm. Left: On-axis field. Right: 10" off-axis field.

4 MECHANICAL DESIGN

We have finalised the mechanical design of the AO system. We have designed the system to fit on an optical bench of 1.8 $\times$ 1.2 m in size. The optical bench is located in the climate controlled clean room approximately 20 m from the telescope.

We have used commercial parts for the system to simplify the design and reduce costs. As AOI interfaces with the

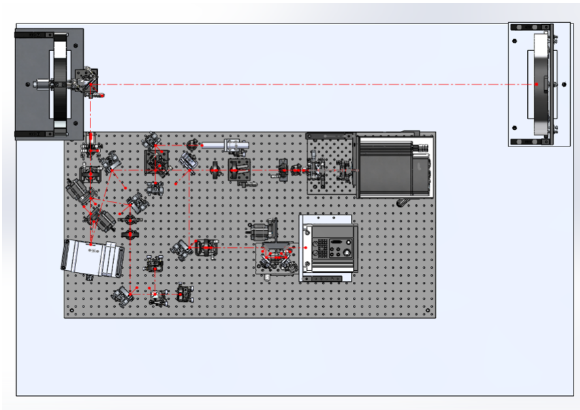
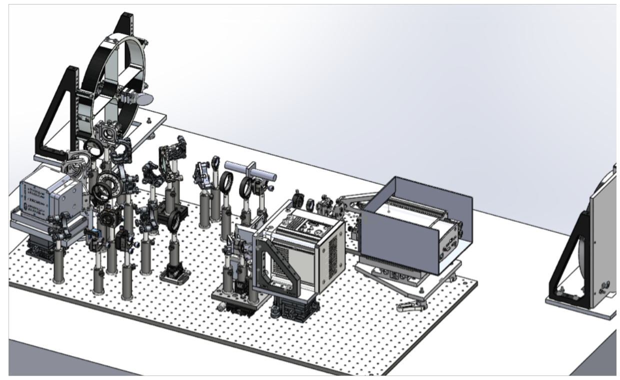

Fig. 5: Mechanical layout of AOI. Left: Top view of the mechanical layout. Right: Trimetric view of the mechanical layout

telescope via a Coudé path we did not have to design the system to be gravity invariant, therefore commercial parts can provide the appropriate stability.

The mechanical design of the system is shown in Fig. 5. The main components of the AO system (DM, WFS and imaging camera) have been placed on a breadboard which is 600 $\times$ 1200 mm in size. The beam expander primary and secondary mirror mounts are located directly on the optical bench.

We have designed the wavefront sensor to be interchangeable with another AO system, so the same camera can be used on two systems. The wavefront sensor mount includes the OCAM2k EMCCD camera, microlens array, and two relay lenses. The WFS is mounted kinematically with three points, this mount can be lifted off the bases and moved to another system quickly with little adjustment required.

5 FUTURE DEVELOPMENT

We are currently building the AO system and will be integrating onto the telescope and beginning operations in early 2018. We will operate the system NGS mode and characterisation data obtained will be provided to partners in the Space Environment Research Centre (SERC) for improving orbital prediction models. We will also conduct surveys to identify high area to mass ratio (HAMR) objects which could be used for orbit modification from a ground based laser system.

In 2019 we will have a laser guide star facility operational on the telescope. AOI will be upgraded to work with a LGS and we will conduct on-sky operations in LGS mode. The addition of the LGS will enable us to image fainter objects and we can compare the performance of the system with the NGS mode.

6 CONCLUSION

We have designed an adaptive optics system capable of characterising objects in LEO and tracking satellites in GEO. The AO system features a 277 actuator deformable mirror and Shack Hartmann wavefront sensor operating at 2 kHz. We have improved imaging performance by utilising custom lenses to reduce optical aberrations over a wavelength range of 600 - 950 nm. We have implemented a 75 arcsecond field of view to assist in finding targets quickly, and we then switch to the standard imaging mode. We have completed the mechanical design of the AO system and are currently building the system and we will begin operation of the system in early 2018.

7 ACKNOWLEDGEMENT

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