Adaptive Optics for Satellite and Debris Imaging in LEO and GEO

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ABSTRACT

The Research School of Astronomy and Astrophysics (RSAA) at the Australian National University has developed and Adaptive Optics (AO) system for satellite and debris imaging in low Earth orbit (LEO) and geostationary orbit (GEO). In LEO the size, shape and orientation of objects will be measured with resolution of 50 cm for objects at 800 km range at an 800 nm imaging wavelength. In GEO satellite position will be measured using precision astrometry of nearby stars. We use an AO system with a deformable mirror (DM) of 277 actuators and Shack-Hartmann wavefront sensor operating at 2 kHz. Imaging is performed at a rate of >30 Hz to reduce image blur due to tip-tilt and rotation. We use two imaging modes; a high resolution mode to obtain Nyquist sampled images and a acquisition mode with 75 arcsecond field of view to aid in finding targets.

1   INTRODUCTION

Space debris poses a significant risk to future satellite operation which has become a vital component of modern society. Careful management of the space environment is needed to avoid a Kessler syndrome[1], where a single collision can cause a catastrophic cascade of debris and render the space environment unusable.

Optical measurements can provide precise position tracking of satellites and debris. Satellite laser ranging (SLR) systems are capable of position measurement with millimetre accuracy[2], provided the satellites are cooperative and feature retroreflectors. Debris laser ranging (DLR) is more difficult as the target is uncooperative, and precision is limited to the order of 1 m[3, 4].

Passive measurements can be used to track objects far away, where photon return from SLR systems is too low. Optical imaging also provides a method to track objects, provided they are illuminated by the sun. Position is measured by image centroiding and accurate telescope pointing information.

Orbital prediction after tracking is needed to anticipate possible collisions between satellites and debris, allowing avoidance measures to be taken. Predicting the orbit of an object after tracking is difficult due to the number of parameters which influence the orbit[5]. Size, shape and orientation can impact how an object will react to atmospheric effects and solar radiation pressure. RADAR cross-section can give an indication of object size[6], however

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specific characteristics cannot be obtained. High resolution optical images can provide information needed for object characterisation[7]. The combination of accurate tracking from SLR and object characteristics can allow for high accuracy predictions.

Observation through optical telescopes provide a means of characterising the size, shape and orientation of objects. Ground based telescopes must look through the atmosphere which degrades image quality due to atmospheric turbulence. These atmospheric effects limit the resolution of the system, which effectively reduces the aperture of the telescope to the order of 10 cm. This causes blurring, preventing feature recognition of satellites and debris. Adaptive optics (AO) can be used to correct the distortions induced by the atmosphere and produce near-diffraction limited images.

The Research School of Astronomy and Astrophysics (RSAA) at the Australian National University have been developing AO systems for space situational awareness. The Adaptive Optics Imaging (AOI) system will capture images of satellite and debris in low Earth orbit (LEO) and geostationary orbit (GEO). This paper details the expected performance and optical design of the AOI system.

2   AOI: ADAPTIVE OPTICS IMAGING

The AOI system will operate on a 1.8 m telescope located at Mt. Stromlo Observatory, Canberra, Australia.

We will operate AOI in two modes; natural guide star (NGS) and laser guide star (LGS) mode. In NGS mode the target object is used as the guide star for the AO system. Reflected sunlight from the object is split between the Shack-Hartmann wavefront sensor and the imaging camera. In LGS mode an artificial beacon is created at 90 km altitude with a 589 nm laser, light from this artificial star is sent to the wavefront sensor while all reflected sunlight from the target object is used for imaging. In LGS mode fainter objects may be imaged, increasing the likelihood of detecting small debris.

The RSAA is developing a laser guide star facility (LGSF) to operate on the 1.8m telescope. This development is ongoing. We will operate the AO system in NGS mode until the LGSF is complete, and once the LGSF is available operation in LGS mode will commence.

2.1   LEO IMAGING

AOI will be used for performing object characterisation on satellites and debris in LEO. The requirements of the system for LEO imaging are listed in Table 1.

Table 1: LEO Imaging Requirements

Specification	Requirement
Strehl	30% at 800 nm
Minimum range	700 km
Operational seeing	<2 arcseconds

The 1.8 m telescope has a diffraction limit of 0.09 arcseconds at 800 nm. With the AO system this telescope will be able to resolve features 50 cm in size for objects at a range of 800 km. Features such as the satellite bodies and solar panels will be resolvable with AOI when imaging objects in LEO. Resolving such features can provide the size, shape and orientation of objects which can be used to refine orbital parameters and improve orbital predictions. Rotational rates can also be measured through light curves[8]. The intensity observed will vary due to changes in the surface area reflecting sunlight to the telescope. Observing these variations over time will allow the rotational rate to be measured and discern if the rotation is increasing, decreasing or stable.

Fig. 1 shows a simulation of the Hubble Space Telescope (HST) imaged with the AOI system with and without AO correction. Without AO correction the features of the satellite are not resolved. With AO correction the shape of the satellite body can be seen more clearly and smaller features on the side of the body can be seen.
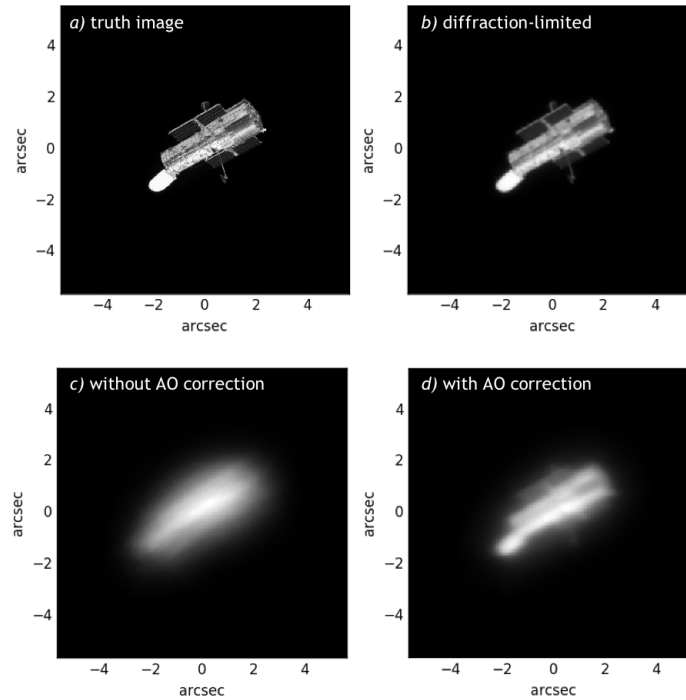
Fig. 1: Simulated imaging of the Hubble Space Telescope with AOI. a) Truth image of Hubble Space Telescope, which is a perfect image of HST. b) Diffraction limited image with the 1.8 m telescope and no atmospheric effects. c) Simulated image with no AO correction. d) Simulated image with correction from AOI system.

AOI will be used to conduct surveys for cataloguing and identifying objects in LEO. A detailed catalogue of satellites and debris can provide an important function in the management of the space environment. Surveys may be used to identify high area to mass ratio (HAMR) objects suitable for orbit modification through photon pressure. The RSAA is developing an AO system to demonstrate debris orbit manoeuvre with a ground based laser[9], and these experiments require light objects with a large surface area and ideal orientation to maximise the illuminated area. Identifying ideal targets for this orbit manoeuvre will assist in a successful demonstration of the system.

2.2   GEO IMAGING

AOI will be used for satellite and debris position measurements for objects in GEO. The 1.8m telescope is not able to resolve objects at GEO, however these objects can be imaged to perform accurate position measurements. The requirements of the system for GEO imaging are listed in Table 2. We can achieve a strehl ratio of 50% in GEO, the telescope slew rate is much smaller than required in LEO so higher strehl ratios are possible.

Table 2: GEO Imaging Requirements

Specification	Requirement
Strehl	50% at 800 nm
Positional accuracy	1 m
Object magnitude	<15
Field of view	>15 arcseconds
Operational seeing	<2 arcseconds

Satellite position at GEO will be measured by capturing images as it passes within 15 arcseconds of a reference star. The centroid of the satellite and reference star are measured and the position of the satellite obtained through astrometry. Fig 2 shows the concept of operation for GEO imaging.
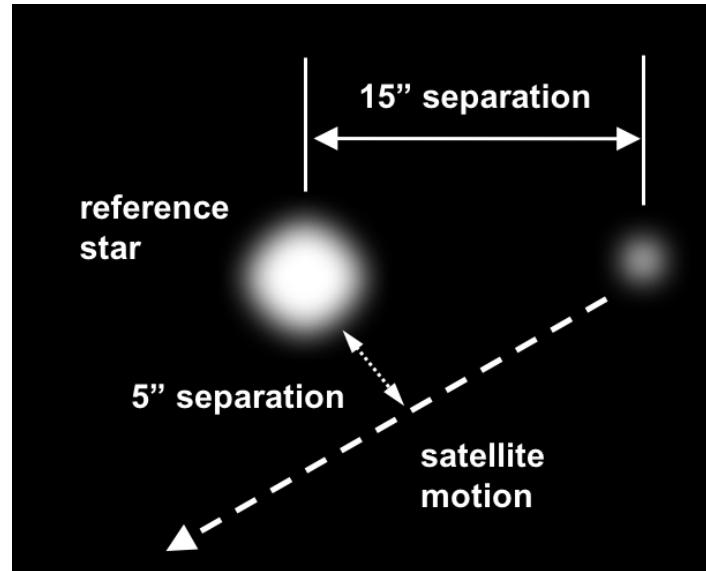
Fig. 2: GEO imaging operational concept. The satellite will be imaged while it is within 15 arcseconds of the reference star. The satellite passes within 5 acrseconds of the reference star during the imaging period.

We will use stars from the Gaia catalogue, which will have its first data release in September 2016, as the reference stars for GEO measurements. The Gaia catalogue will provide reference stars with a positional accuracy of up to 20 microarcseconds allowing for positional measurements on objects brighter than magnitude 15. This magnitude is equivalent to a 1 m^2 object at GEO.

3   OPTICAL DESIGN

The design of an AO system is influenced by the telescope size and atmospheric conditions at the site. The wavefront sensor (WFS) is a Shack-Hartmann featuring an OCAM2k EMCCD camera. The specifications of the AO system are summarised in Table 3.

Table 3: AO Specifications

Parameter	Specification
DM actuator grid	17×17
WFS subapertures	16×16
Pixels per subaperture	12
WFS loop rate	2 kHz

We have chosen an ALPAO DM277 deformable mirror (DM) with actuators in a 17×17 grid. The choice of DM was based on simulations to measure performance of the AO system with different configurations. These simulations showed that a larger number of DM actuators would result in decreased performance because of a lower signal to noise ratio at the wavefront sensor. An AO system with Fried geometry would require the light to be split between more subapertures, hence decreasing the amount of light available to each subaperture. We have balanced the wavefront error introduced by the DM and wavefront sensor to obtain the best possible performance in the design conditions of 2 arcsecond seeing.

The optical layout of the AO system is shown in Fig. 3. Light collected by the telescope is collimated by the secondary mirror and is directed to the AO system via a 20 m long Coudé path. A beam expander resizes this beam with a parabolic mirror and two collimating lenses to 24.5 mm, the DM aperture size. The DM is placed in a conjugate pupil plane to the telescope primary mirror. The beam reflected off the DM is passed to a dichroic beamsplitter. In NGS
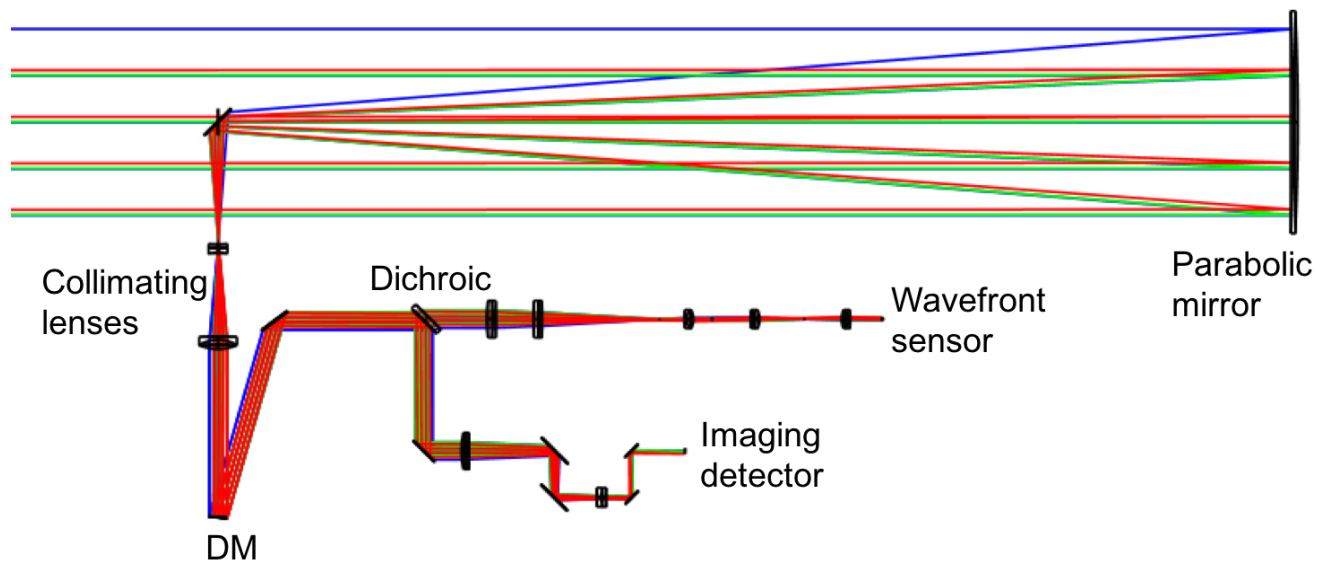
Fig. 3: Optical layout of AOI. The beam from the Coudé path is reduced in size by a parabolic mirror and collimating lens to the DM pupil size. Light is split between the wavefront sensor and imaging detector by a dichroic beamsplitter.

mode wavelengths between 450 and 800 nm are transmitted to the wavefront sensor (WFS) and wavelengths between 800 and 1000 nm are reflected to the imaging camera. When using LGS mode only 589 nm light, the wavelength of the LGS, will be sent to the wavefront sensor. In LGS mode wavelengths between 600 and 1000 nm are sent to the imaging camera.

The imaging camera is a Nuvu HNu 512 EMCCD camera which has a frame size of 512×512 pixels and can operate at up to 60 Hz. We run the imaging camera at >30 Hz to reduce the blurring caused by tip-tilt and object rotation. Image motion from tip-tilt is processed in real time, with corrective commands sent to the DM and telescope to stop the image drifting on the detector.

High speed images obtained are shifted and stacked to improve final image quality. We will also utilise lucky imaging techniques where only the best quality images will be selected for shifting and stacking.

The imaging arm will operate in two modes; a high resolution mode and wide field of view acquisition mode. The uncertainty in satellite orbit makes it difficult to acquire the target, and the satellite will be in range for a matter of minutes requiring fast acquisition. To assist in finding satellites an acquisition mode is used with a field of view of 75 arcseconds, which reduces the time needed to search for the satellite. Once the target is acquired the high resolution mode is enabled by moving a second lens into the beam path to increase the effective focal length. This is done through a high precision stage. The detector remains in a fixed position and path length differences between the two modes are accounted for with fold mirrors. To maximise the period that the object is imaged the transition between imaging modes is less than 5 seconds. The layout of the two imaging modes are shown in Fig. 4.

In high resolution mode the plate scale is 0.044 arcsecond per pixel at 800 nm, allowing for Nyquist sampled images to be captured. The small plate scale needed to capture Nyquist sampled images limits the high resolution mode to a 22 arcsecond field of view.

Table 4 compares the on-sky diameter available with each of the imaging modes in LEO and GEO. The larger field of view acquisition mode provides a >3 times on-sky diameter, which allows a much wider search area for acquiring the target and a higher likelihood of finding the object.
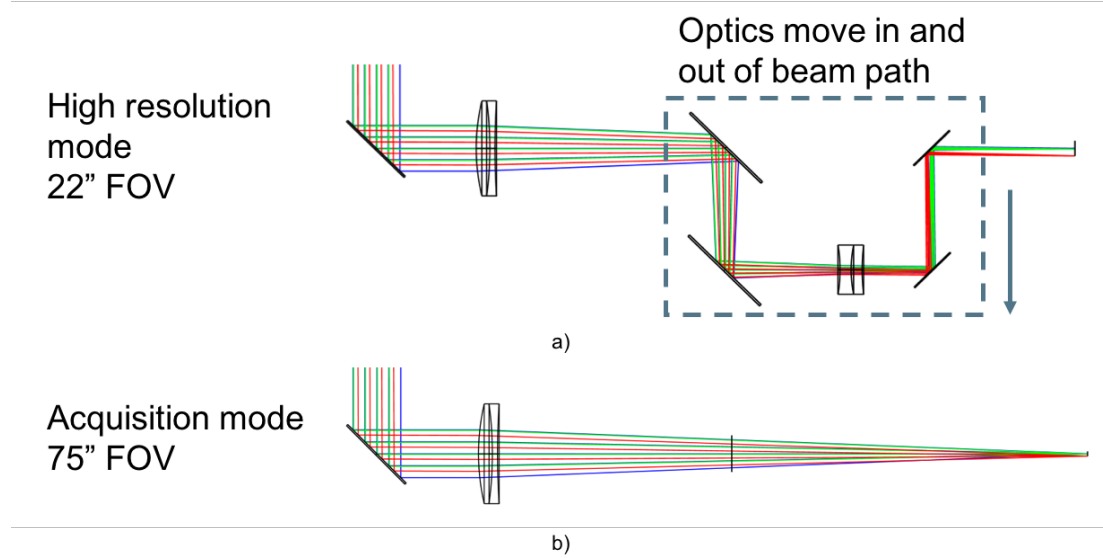
Fig. 4: Imaging modes of AOI: a) High resolution imaging mode with 22 arcsecond field of view. The lens and mirrors contained within the dashed box are mounted on a linear stage and move in and out of the beam path to change the imaging modes. b) Acquisition imaging mode with 75 arcsecond field of view. The lens and fold mirrors mounted on the stage are moved out of the beam path to give a smaller effective focal length.

Table 4: On-sky imaging area diameter for imaging modes in LEO and GEO

Imaging mode	High resolution (22" FOV)	Acquisition (75" FOV)
LEO	87 m	300 m
GEO	4 km	13 km

4   CONCLUSION

We have designed an AO system for imaging satellites and debris in LEO and GEO on a 1.8 m telescope. Imaging objects in LEO is used for size, shape and orientation characterisations, with resolution of 50 cm at 800 km range at 800 nm imaging wavelength. Imaging objects in GEO is used for positional measurements of satellites using an astrometric reference star from the Gaia catalogue. We expect positional accuracy of 1 m for objects brighter than magnitude 15 in GEO.

We presented the optical design of the AOI system, using a Shack-Hartmann wavefront sensor with 16×16 subapertures and a DM with 17×17 actuator grid. Imaging is performed with a Nuvu HNu 512 EMCCD camera operating at >30 Hz. We image at high rates to remove blurring due to tip-tilt and rotation. The high imaging rates also allow for lucky imaging techniques to be used, and we select the best quality images to shift and stack to obtain improved image quality.

The optical design features two imaging modes; a high resolution mode for Nyquist sampled images and 22 arcsecond field of view, and an acquisition mode with 75 arcsecond field of view for fast acquisition of the target.

5   ACKNOWLEDGEMENT

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