Satellite imaging with adaptive optics on a 1 m telescope

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ABSTRACT

The Research School of Astronomy and Astrophysics at the Mount Stromlo Observatory in Canberra, Australia, have been developing adaptive optic (AO) systems for space situational awareness applications. We report on the development and demonstration of an AO system for satellite imaging using a 1 m telescope.

The system uses the orbiting object as a natural guide star to measure atmospheric turbulence, and a deformable mirror to provide an optical correction. The AO system utilised modern, high speed and low noise EMCCD technology on both the wavefront sensor and imaging camera to achieve high performance, achieving a Strehl ratio in excess of 30% at 870 nm. Images are post processed with lucky imaging algorithms to further improve the final image quality. We demonstrate the AO system on stellar targets and Iridium satellites, achieving a near diffraction limited full width at half maximum. A specialised realtime controller allows our system to achieve a bandwidth above 100 Hz, with the wavefront sensor and control loop running at 2 kHz.

The AO systems we are developing show how ground-based optical sensors can be used to manage the space environment. AO imaging systems can be used for satellite surveillance, while laser ranging can be used to determine precise orbital data used in the critical conjunction analysis required to maintain a safe space environment. We have focused on making this system compact, expandable, and versatile. We are continuing to develop this platform for other space situational awareness applications such as geosynchronous satellite astrometry, space debris characterisation, satellite imaging, and ground-to-space laser communication.

INTRODUCTION

Optical telescopes are increasingly being used for space situational awareness (SSA)[1] for their accuracy in tracking and ability to survey wide fields. The goal of SSA is to track as many orbiting objects as possible, both active satellites and debris in order to avoid collisions and a Kessler syndrome[2]. These tracked objects are accumulated into a precise catalogue which contains up to date and highly accurate data needed to predict any possible conjuncture. Active satellites can be warned to perform debris avoidance manoeuvres, and possible collisions between debris objects determined in advance. Optical telescopes have been used for SSA in the form of satellite laser ranging (SLR)[3, 4], where ranging information is used to predict any possible close approaches between two objects[5]. In order to have confidence in these orbital predictions, more advanced models are being developed which take into account not only the ranging information, but also the shape, mass, and orientation of the tracked body[6]. These factors greatly influence the fidelity of the orbital propagation model as orbit perturbations from atmospheric and solar radiation pressure are heavily influenced by object size and shape, particularly if they change with time[7].

The Research School of Astronomy and Astrophysics are developing Adaptive Optic (AO) systems to improve SSA with optical telescopes. We have developed an AO system for a 1 m telescope which is capable of imaging satellites and debris in orbit with Strehl ratio in excess of 30%. With this system we are able to resolve features down to 85 cm in size at 1000 km range. This paper describes the development of this AO system, and first on-sky results.

ADAPTIVE OPTICS

Turbulent layers in the atmosphere create distorted wavefronts of light which reduce the resolving power of ground based optical telescopes. Instead of producing higher resolution images, large telescopes are able to capture more light than small telescopes, but their resolution is limited by the scale of the turbulence r_0. A good site for an optical telescope may have an r_0 of 12-15 cm, while a poor site may have r_0 of 5 cm. No matter the diameter of the telescope, the atmospheric turbulence will dictate the resolving power. Adaptive optics is a technique of correcting atmospheric turbulence by measuring the distorted wavefront, and using an active optical element such as a deformable mirror (DM) to flatten the wavefront and restore near diffraction-limited imaging.

Fig. 1 shows the operating principle of an AO system. Light from a guide star is collected by the telescope, and has a distorted wavefront caused by atmospheric turbulence. A wavefront sensor measures this distortion and provides feedback via a control computer to a DM. The next incident wavefront is corrected by the DM after reflection, and the wavefront is measured again. A dichroic beamsplitter is used to separate wavelengths of light from the guide star and target, so that wavefronts can be measured at the same time images are taken. Such an AO system is known as a 'closed loop' AO system, because there is a control loop operating between the wavefront sensor and DM.

Our AO system is a compact and high performance system using modern high stroke DM and low noise high rate EMCCD cameras for imaging and wavefront sensing. We are able to track satellites down to magnitude 10 with Strehl in excess of 20% in median seeing.

We use the satellite as a natural guide star (NGS) on a Shack-Hartmann wavefront sensor with a closed loop rate of 2 kHz. Our system meets the performance requirement of 20% Strehl at a nominal orbiting altitude of 1000 km, but will also operate on objects down to 600 km. Below this altitude the telescope slew rate is so great that even at 2 kHz the AO system does not have the bandwidth to provide enough correction. We have developed a system for processing imaging data in real time to remove the need for derotating optics and large stroke tip-tilt correction.

ADAPTIVE OPTICS SYSTEM DESIGN

This AO system is designed to image satellites in low Earth orbit (LEO) and achieve a Strehl ratio of 20% for objects of visible magnitude 10 up to an altitude of 1000 km.The system is designed to operate in good seeing, with r_0 of 12 - 15 cm and wind speed of 8 - 10 ms^{-1}. Our system can accomodate poor seeing (2 arcseconds), and can take advantage of good seeing conditions to further increase system performance.

Fig. 2 shows the schematic for the AO system, which sits on an optical bench in a temperature controlled Coudé laboratory. Light from the telescope is directed to the AO system as a collimated beam via a Coudé path. A beam expander reduces the beam size from 250 mm to 12.5 mm, and the pupil is imaged onto the reflective DM

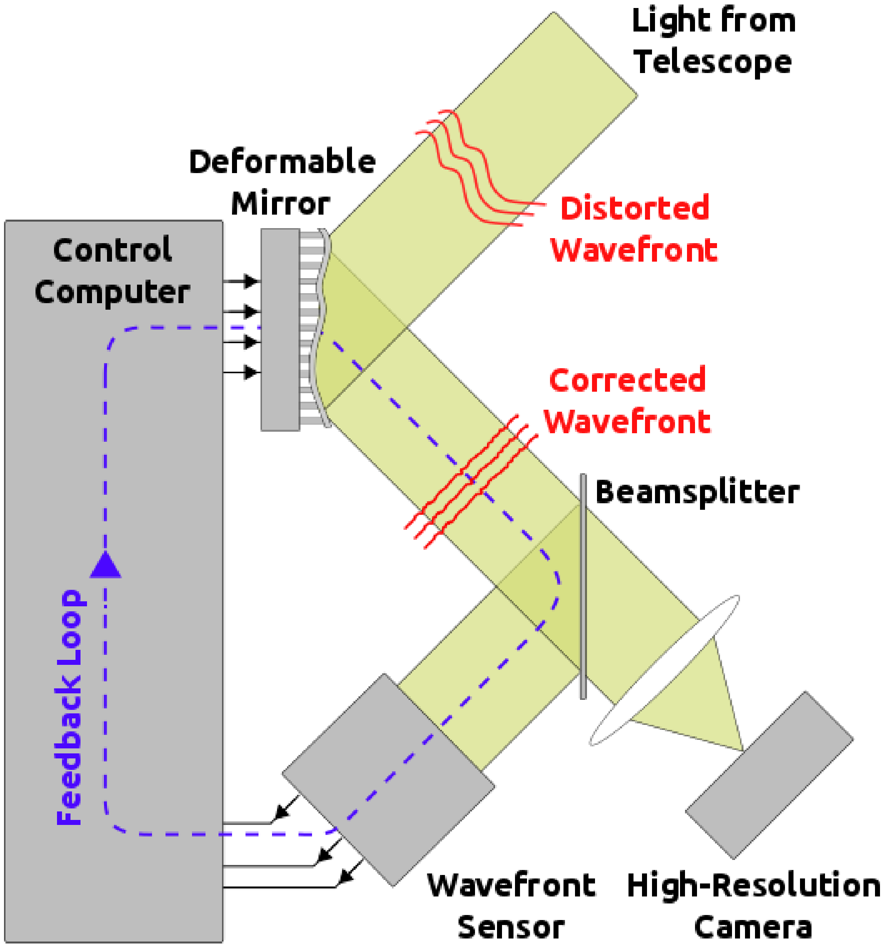

Figure 1: AO system control loop: distorted wavefronts from a guide star are corrected by the deformable mirror, and residual wavefront aberrations measured by the wavefront sensor. A beamsplitter is used to split light between the wavefront sensor and imaging camera.

face sheet. The light is split with a dichroic beamsplitter, with wavelengths from 450 - 800 nm being transmitted to the WFS, and 800 - 1000 nm reflected to the imaging camera. A calibration source is inserted into the system with a mechanical flip mirror, for automated system calibration and optimisation.

The wavefront sensor is a Shack-Hartmann with 8×8 subapertures and an OCAM2k camera which can operate at up to 2 kHz with $< 0.4e^{-}$ readout noise. The DM is an ALPAO DM-69 deformable mirror specified to operate at up to 2 kHz with 30 μm of full stroke. The large stroke on the DM allows us to correct a large amount of tip-tilt without compromising high-order correction. The Raptor Falcon EMCCD imaging camera operates at up to 60 Hz, and images are post-processed using a shift-and-stack algorithm combined with lucky imaging to reduce image blur due to tip-tilt. Field rotation is also removed in this processing, avoiding the ned for a mechanical derotation device.

This system is designed for a 1 m telescope, with an imaging wavelength range of 800-950 nm. The diffraction limit is 0.18 arcseconds at 850 nm which will enable the system to resolve features approximately 85 cm in size at a range of 1000 km. Satellites such as the Iridium constellation have features on the order of 1 - 6 m, not including solar panels. Fig. 3 shows simulated images of an Iridium satellite under (a) seeing limit with r_0 of 15 cm, (b) AO correction, and (c) the original image used for the simulation. The body of the Iridium satellites is approximately 1 m in width, and 6 m in length,

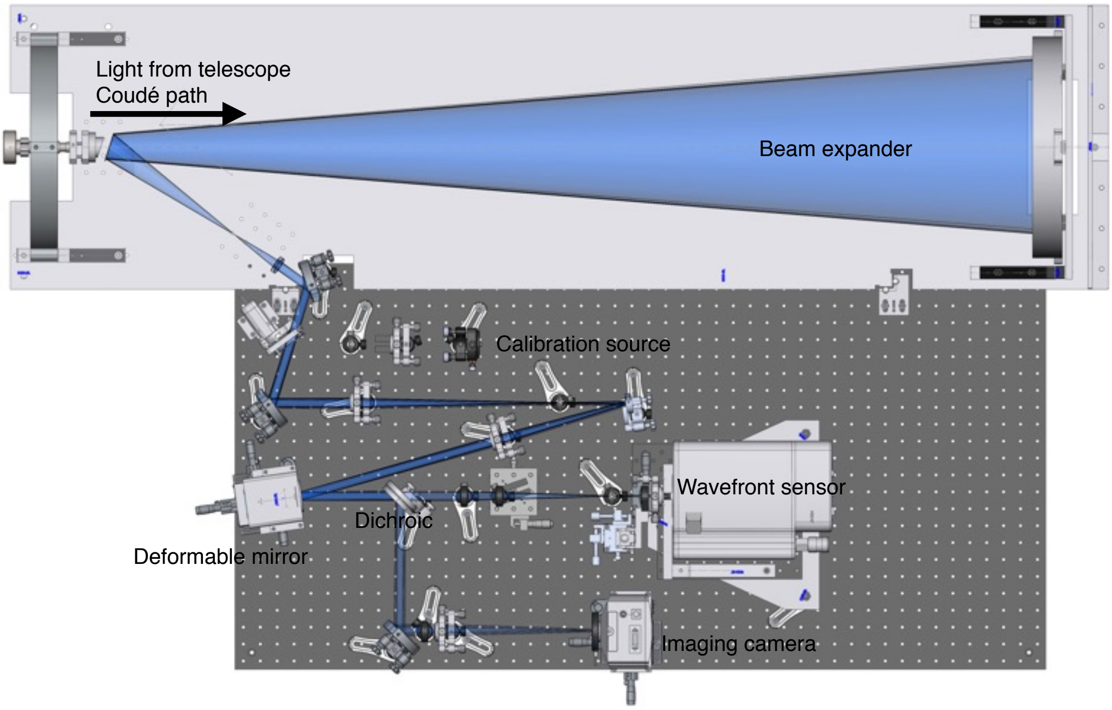

Figure 2: AO System layout. Light from the telescope Coudé path is magnified by a reflective beam expander, and conditioned by optics before reflecting from the deformable mirror. A dichroic beamsplitter splits wavelengths between the wavefront sensor and imaging camera.

which subtend an angular size of 0.2 and 1.2 arcseconds respectively at a range of 1000 km.

Satellite acquisition is difficult without a wide field telescope because the TLEs used to track satellites can be days or even weeks old, and so the imaging camera is also used for satellite acquisition. The full frame is read out in a 4×4 binned mode to achieve a frame rate of up to 25 Hz, giving a field of view of 90 arc seconds. Once a target is acquired the camera is switched to a windowed mode reading out a region 23 arcseconds in size.

ON-SKY RESULTS

In December 2015 we operated the system on-sky during the factory acceptance test, using the EOS 1 m SLR telescope located at the Mount Stromlo Observatory in Canberra, Australia. The goal of the test was to verify system performance against top level requirements. The AO system was first tested on bright stellar sources. Fig. 4 shows images of a magnitude (V band) 3.86 star with (a) the AO loop open, and (b) the AO loop closed. With the AO loop open the FWHM is approximately 2.5 arcseconds due to the poor seeing on the night. With the AO loop closed the light is concentrated in a single core and the first diffraction ring is visible. The closed loop FWHM is 0.27 arcseconds. The images are produced with a very simply lucky imaging algorithm which stacks the brightest 10% of images, which produces higher Strehl than obtained with an instantaneous image. Image motion is also removed within the lucky imaging algorithm. The signal to noise ratio is much higher in Fig. 4(b) because several images are stacked, and the light is concentrated in only a few pixels. The Strehl ratio of the Fig. 4(b) is 27% at 850 nm.

Fig. 5 shows the closed loop resolution of a binary star with a visible magnitude

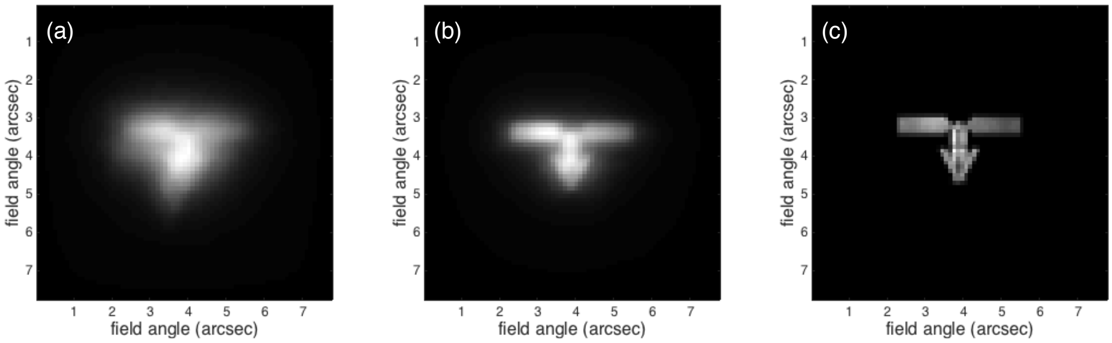

Figure 3: Simulated images of an Iridium satellite taken by 1 m telescope at 850 nm under (a) seeing limited with r_0 of 15 cm, (b) AO correction, and (c) the original image used for the simulation

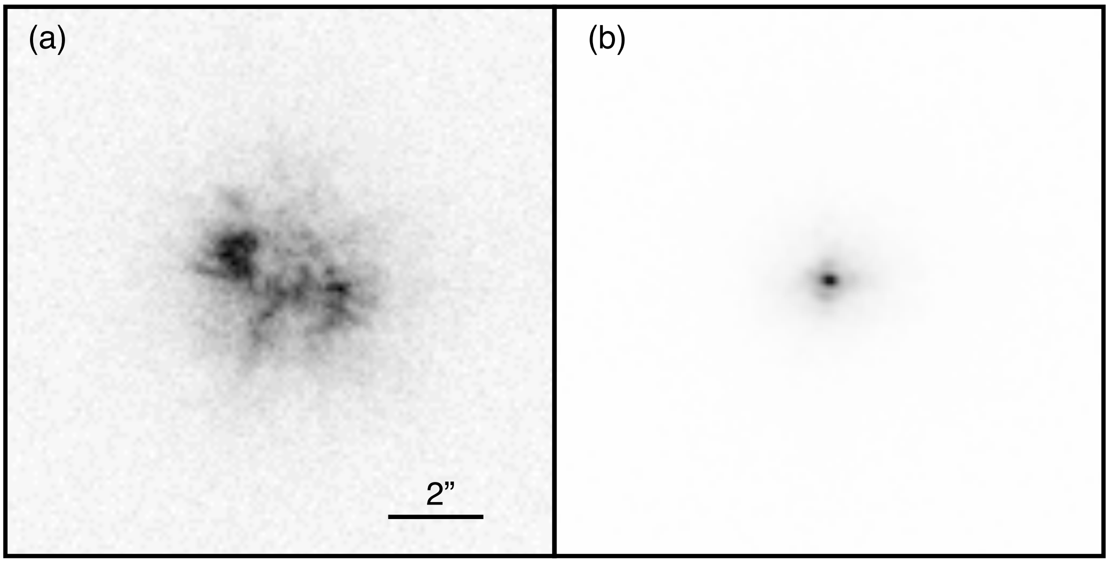

Figure 4: Images of a stellar object with visible magnitude of 3.86. Images of the star with the AO loop (a) open, and (b) closed show the effectiveness of the AO system in compensating atmospheric turbulence.

3.27. The star separation is approximately 0.3 arcseconds. The image FWHM with the AO loop closed is 0.25 arcseconds.

In September 2016 we successfully resolved several satellites with the AO loop closed. Fig. 6 shows images of Iridium-86 (a) without AO correction, and (b) with AO correction. Without the AO loop closed the light is spread with a FWHM of 2.48 arcseconds, and with the AO loop closed the light is concentrated in a few pixels with a FWHM of 0.66 arcseconds. This is slightly larger than a fully resolved point source in these seeing conditions, and so the satellite has been resolved.

Fig. 7 shows several images taken over a period of 30 seconds. These images have had all field rotation removed with software, and the rotation of the satellite is clearly visible over this time period. The length of the satellite as measured is 4.6 arcseconds. The two solar panels are clearly visible as lobes around a bright central feature which is the downward facing body. This satellite has an apogee of 566 km, and perigee of 555 km. From these measurements we can approximate the solar panel extent to be approximately 12-15 m. In the future we hope to tie ranging and orbital information to our data acquisition so that resolved features can be dimensioned.

Fig. 8 shows images of the Swarm-C satellite with AO correction on. This satellite

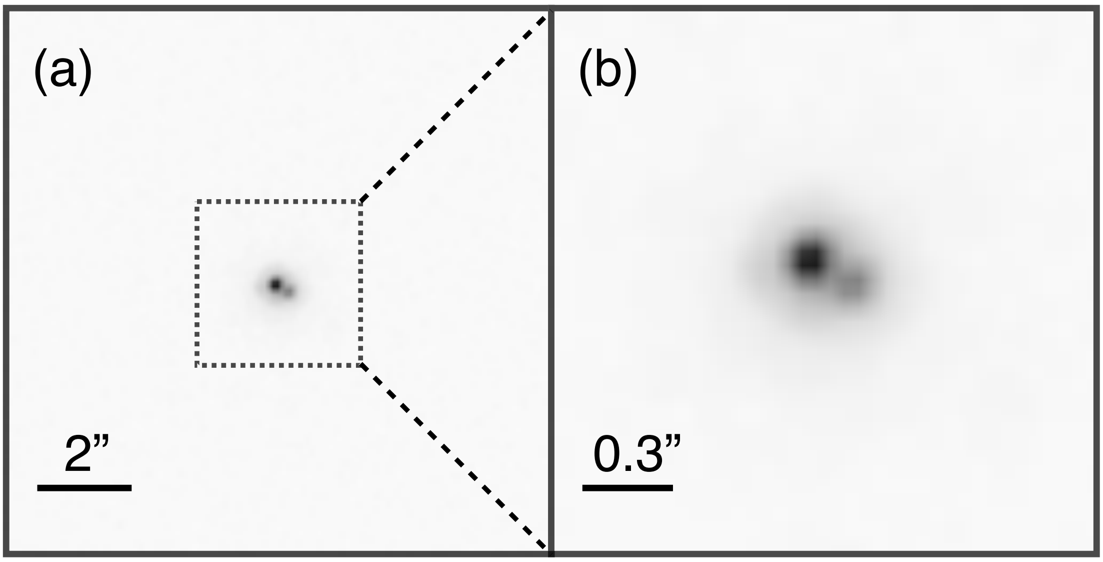

Figure 5: (a) AO Loop closed on a binary star with separation of 0.31 arcseconds, (b) enlarged image clearly shows resolution of both stars. The FWHM of the image is 0.25 arcseconds.

is a long pencil-like structure and we resolve the narrow side as 0.8 arcseconds, with a length of 4.1 arcseconds.

We were able to demonstrate the systems capability to image faint objects by closing the AO loop on a visible magnitude 9.3 star. In seeing conditions of 2.7 arcseconds we achieved a Strehl ratio of 14%. When compared with simulations under similar conditions we can predict that we will achieve more than the 20% Strehl requirement under better seeing conditions with r_0 12 - 15 cm.

FUTURE SYSTEM DEVELOPMENT

The AO systems we design are constrained by available hardware and budget. In order to achieve the optimal configuration of hardware for a given application we must first know about the site atmospheric characteristics. We are developing a stereo scintillation detection and ranging (SCIDAR) system which measures the atmospheric turbulence profile C_n^2. We can then optimise our system design to take advantage of the site characteristics, and have confidence in our atmospheric simulation models.[8]

We are in the critical design phase of an improved AO system for SSA for the 1.8 m telescope operated by EOS at Mount Stromlo in Canberra, Australia as part of the Space Environment Management Cooperative Research Centre (SERC), of which The ANU is a partner. The system is called the Adaptive Optics Imaging system and will have higher performance, along with better resolution. The system will be used for imaging LEO objects, and also high precision position determination of satellites and debris in the Geosynchronous belt. This system will be capable of operating in natural guide star mode, as well as with a laser guide star. The laser guide star system will provide much more flexibility on which targets are observed, and will provide better AO system performance by allowing more light to reach the imaging camera. We will be able to track objects in Geosynchronous orbit and determine their position to an accuracy of 1 m, by using high precision astrometry of a nearby star.[9]

We are currently in the preliminary design phase of upgrading an existing AO system[10] to achieve remote manoeuvring of an orbiting object. A high power ground based laser coupled with AO can achieve high enough flux incident on an orbiting body to produce significant photon pressure. This system is aimed at demonstrating remote

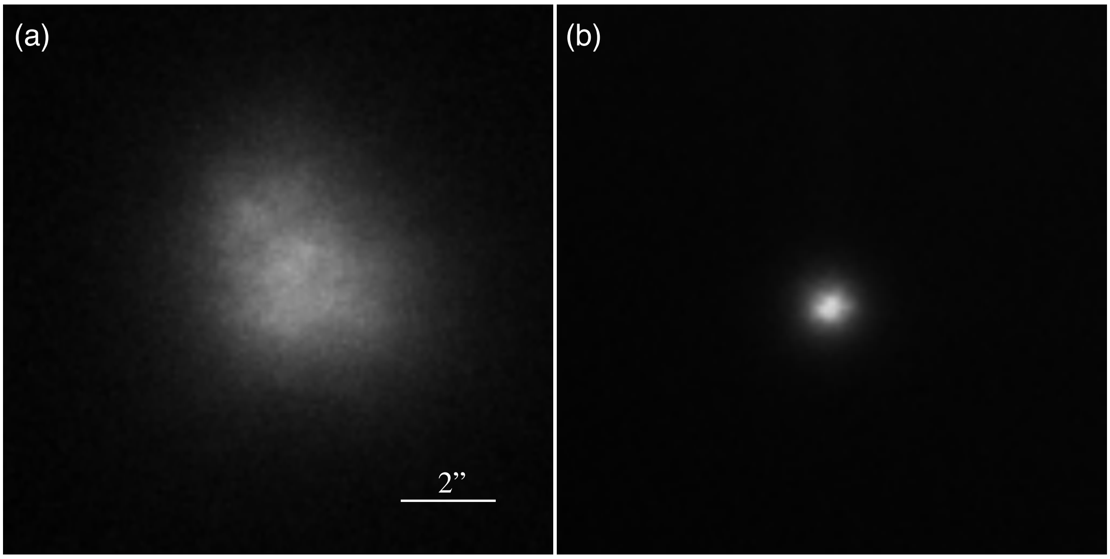

Figure 6: Images of Iridium-86 (a) without AO correction, and (b) with AO correction.

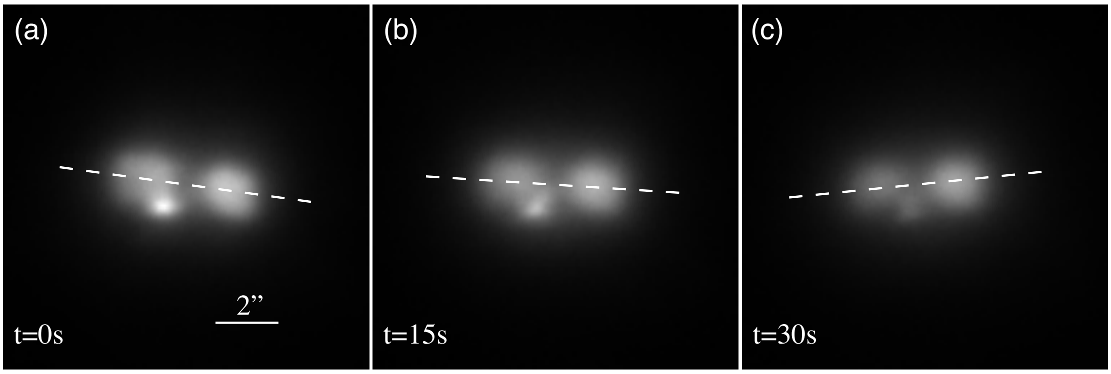

Figure 7: AO corrected images of Resurs-DK1 satellite shows rotation of satellite after all field rotation is removed at (a) $t = 0$ s, (b) $t = 15$ s, and (c) $t = 30$ s.

manoeuvring and will begin with orbit based flux measurements to refine AO system performance.[11]

CONCLUSION

We have shown the development and first on-sky results of an AO system for LEO satellite imaging. The AO system uses a Shack-Hartmann wavefront sensor and deformable mirror both running at 2 kHz, and has achieved Strehl ratio in excess of 30% on stellar sources. We were able to resolve a close binary star system with star separation of 0.3 arcseconds with an image full width half maximum of 0.25 arcseconds. We were able to resolve images of several satellites, showing clear images of features such as solar panels and main bodies. We observed satellite rotation and are able to measure the full width half maximum to determine approximate satellite size. We demonstrated the AO system performance to a visible magnitude of 9.3. We are continuing to develop AO systems and metrology for atmospheric turbulence for SSA applications, including satellite imaging and remote manoeuvre using photon pressure.

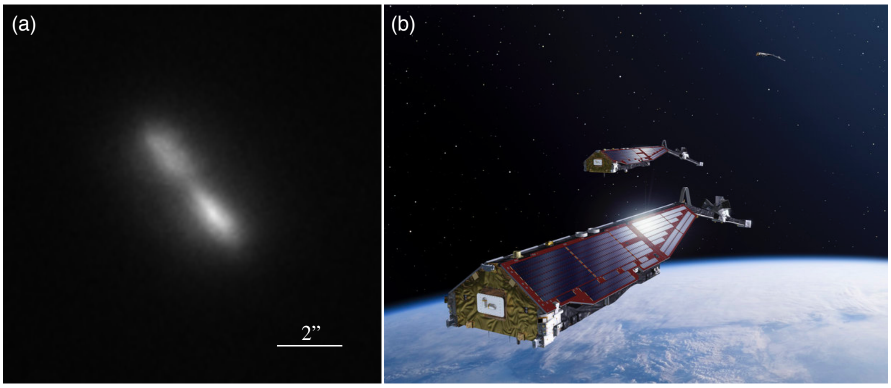

Figure 8: (a) AO corrected image of Swarm-C satellite. (b) an artist?s impression of Swarm-C (credit: ESA-P. Carril ESO).

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