Adaptive optics for satellite imaging and space debris ranging

Francis Bennet, C. D'Orgeville, I. Price, F. Rigaut
Research School of Astronomy and Astrophysics, Australian National University, and Space Environment Research Centre, Canberra, Australia

I. Ritchie, C. Smith
Electro Optic Systems, and Space Environment Research Centre, Mount Stromlo Observatory, Canberra, Australia

ABSTRACT

Earth's space environment is becoming crowded and at risk of a Kessler syndrome[1], and will require careful management for the future. Modern low noise high speed detectors allow for wavefront sensing and adaptive optics (AO) in extreme circumstances such as imaging small orbiting bodies in Low Earth Orbit (LEO). The Research School of Astronomy and Astrophysics (RSAA) at the Australian National University have been developing AO systems for telescopes between 1 and 2.5 m diameter to image and laser range orbiting satellites and space debris. Strehl ratios in excess of 30% at 800 nm can be achieved for targets in LEO with an AO loop running at 1.5 - 2 kHz, allowing the resolution of small features (<50 cm) and the capability to determine object shape and increase orbit determination accuracy.

INTRODUCTION

Adaptive optics has been used in astronomy for over two decades to increase the efficiency and resolution of astronomical instruments and telescopes. The same technology can be used to improve tracking and ranging of debris objects in orbit, and allow the resolution of small features through imaging. Our increased reliance on satellite technology in so many technical aspects of everyday life put a great number of valuable assets at risk if the space environment isn't managed. An important aspect of managing the space environment is tracking debris objects and satellites precisely.

Optical measurements can provide highly accurate orbital data, with precision down to the decimetre level. High power ground based lasers can be used to track and range debris objects, while operational satellites may be fitted with retroreflectors to aid in ground based laser tracking. Reflected sunlight can be used to image orbiting objects to determine their magnitude, however atmospheric turbulence diminishes the image quality and prevents feature resolution.

The atmosphere contains layers of turbulent flow caused by wind and thermal variation. Light passing though these layers accumulates this turbulence on its wavefront, and the resulting image is distorted. Adaptive optics works to correct these distortions by measuring and correcting deviations from a flat wavefront. Lasers propagated up through the atmosphere are similarly distorted, resulting in the focused spot in space being broadened and distorted. The same AO system which corrects the image of a satellite can also correct the upward propagating laser.

Electro Optic Systems (EOS) have been developing laser ranging systems for objects in orbit at the Mount Stromlo Observatory in Canberra, Australia. EOS operate one of the top performing satellite laser ranging facilities in the world, and have used their expertise to develop a laser ranging system for debris objects. A 1.8 m telescope is used to propagate a pulsed laser through the atmosphere, and collect reflected photons. This system has been demonstrated to track objects down to 10 cm in size and with a range of 2000 km, with a prediction accuracy of the objects position to within 200 m after 24 hours[2].

The Research School of Astronomy and Astrophysics with the Australian National University have been developing an AO system to improve the laser ranging of space debris and for satellite imaging. This system measures wavefront distortions with a laser guide star and corrects the upward propagating laser. Future development of these AO systems for space environment management will be conducted under the Cooperative Research Centre for Space Environment Management (SERC) framework. SERC brings together research and industry partners, building on Australian expertise in space environment management such as laser ranging of space debris to develop new technologies and strategies to preserve the space environment.

SATELLITE TRACKING

Radio Detection and Ranging (RADAR) has been used since its development in the early 1900s to detect and range objects at great distance. The technology consists of a radio transmitter and receiver, along with signal processing electronics to amplify and interpret received signals. RADAR is particularly useful for tracking orbiting objects[3] as the conductive materials they are constructed from are highly reflective in the microwave and radio spectrum. Typical wavelengths range from 2 cm to 6 m, and have the advantage of working in most weather conditions, and at wavelengths to which the atmosphere is transparent. The wavelength does however limit the accuracy and size of objects which can be tracked, and available transmitter power provides a maximum range. Objects in LEO are routinely tracked using RADAR, to maintain the United States Space Surveillance Network database of satellites, rocket bodies, and debris objects larger than 10 cm.

Optical telescopes are more efficient at tracking more distant objects because the sunlight reflecting off them only suffers a $1/r^2$ drop in intensity for a range to target of r. Since radio telescopes must provide their own illumination source, the received power suffers a $1/r^4$ drop in intensity, reducing its efficiency for higher orbits. With the growth in number of debris objects[4, 5] and the growing density of assets in highly valuable orbits require a more accurate method of tracking both space debris and operational satellites. Active ground based tracking using laser illumination and ranging (LIDAR) can also provide highly accurate orbital information. High fidelity conjunction analysis can then be carried out using sophisticated orbital prediction algorithms[6].

Optical tracking falls into one of two categories, passive tracking in which reflected light is used to track and object, or active tracking, where a light source is projected onto the target, and the reflection used for tracking. Passive optical tracking can track objects further away, provided they are illuminated by the sun. Such objects typically have to be large such that they provide a greater signal than the sky background at visible wavelengths, limiting tracking observations to the night. LEO tracking is limited to the terminator period around dusk and dawn, when objects are illuminated and not in Earth's shadow. While the wavelength of light ($\sim 10^{-6}$ m) can in theory provide highly accurate orbital information, refraction by the atmosphere in the form of atmospheric turbulence can distort the image and position of the object quite significantly. Atmospheric absorption also limits the wavelength range available to the visible and near infrared (450-2300 nm). Passive optical tracking is also limited in accuracy and object size by the amount of reflected light from the object due to noise in the detection and amplification process of received photons. Small and low albedo objects may not reflect enough light to provide a high enough signal to noise ratio to achieve accurate information.

Passive optical tracking typically provides a two line element (TLE), which can be used to generate orbital data. This TLE is determined by imaging the target with a detector and using a centroiding algorithm along with accurate telescope pointing information. Atmospheric turbulence will blur the image and cause it to move, which reduces the positioning accuracy.

An active optical tracking system such as LIDAR can be used to track orbiting objects by illuminating a target with a laser beam, and measures the range to the target by accurately timing the round trip of a single laser pulse. This timing provides very accurate ranging information, which can produce positional measurements to less than 1 cm[7]. This increase in accuracy in orbital determination impacts directly on the orbital determination and hence conjunction analysis. Even though this system does not require an image of the target, only a bulk collection of photons, atmospheric turbulence still reduces the system accuracy because the upward propagating laser beam is distorted and blurred by the turbulence, lowering the flux illuminating the target.

LIDAR can be used to track both uncooperative targets such as space debris, and cooperative targets such as satellites fitted with retro-reflectors. The diameter of the ground based telescope determines the size and range limits of trackable targets, due to the diffraction limit and light collecting capability respectively. Cooperative targets are tracked to refine their orbit, and some satellites in highly stable orbits are used for calibration for tracking systems and algorithms.

ADAPTIVE OPTICS FOR LASER RANGING

Actively tracking orbiting objects using ground based optical telescopes is currently the most accurate way of tracking space debris. A ground based laser is propagated through a telescope to meet the target, and reflected photons are used to determine the round trip time of flight. Ranging accuracy is in part determined by how many reflected photons are collected by the telescope. A higher flux on the target will provide more signal at the receiving telescope, increasing the ranging accuracy. While laser power can be increased and telescopes can be made larger to collect more light, atmospheric turbulence will still distort and spread the propagating laser beam. Adaptive optics can be used to counter atmospheric turbulence and increase the flux on a target.

Adaptive optics is a technique of measuring and correcting atmospheric turbulence to increase the performance of a ground based telescope. A guide star, being either a natural stellar source or artificially created laser guide star (LGS), is used to probe the atmosphere above the telescope. A wavefront sensor such as a Shack-Hartmann wavefront sensor is used to measure the wavefront distortions caused by the atmosphere. A deformable mirror (DM) is used to correct these wavefront distortions by controlling the reflective surface shape according to wavefront sensor data. AO systems are widely used in astronomical applications to form near diffraction limited images of astronomical objects.

The non-sidereal tracking required to follow orbiting objects results in high slew speeds (on the order of degrees per second), increasing the relative wind speed and hence turbulence seen by the telescope and AO system. The AO system must therefore run very fast, between 1.5 and 2 kHz, to achieve the performance required to improve laser tracking. The high tracking rate required to track objects in LEO also requires the laser to be directed ahead of the target such that a laser pulse intersects the orbital position of the target when it arrives. The apparent position of the target is similarly off-axis, and the laser guide star is positioned ahead of the ranging laser to probe the region of atmosphere traversed by the ranging laser (Fig. 1).

RSAA and EOS have been jointly developing an AO complimented ranging system

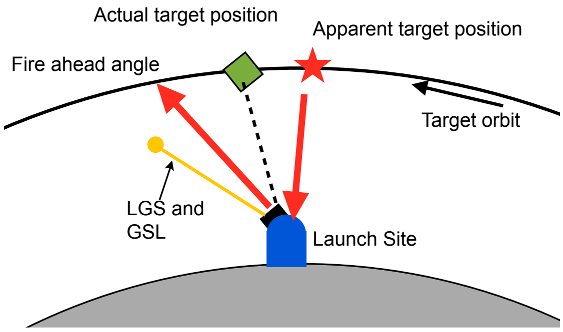

Figure 1: A schematic showing the target in orbit around Earth, passing overhead the ground station for tracking. The guide star laser (GSL) is pointed ahead of the laser, such that the LGS samples the atmosphere through which the probe laser is propagated. The probe laser is angled ahead of the actual target position such that a pulse from the laser will intersect with the targets orbit at the correct time. The reflected laser light appears off-axis in the apparent target position, and reflected sunlight is used here for tip-tilt.

using a 1.8 m telescope located at Mount Stromlo. The system uses the same telescope to project and collect reflected laser light, with an AO system located next to the laser source. The AO system consists of a Shack-Hartmann wavefront sensor with 14×14 subapertures, a deformable mirror with 177 actuators in a square 15×15 grid, and an imaging camera for tip-tilt correction and acquisition. A LGS is used to determine the high order aberrations with the Shack-Hartmann wavefront sensor, and the tip-tilt camera is used for tip-tilt positioning correction. The ranging laser has a pulsed format at a wavelength of 1064 nm and an average power of 200 W.

The Shack-Hartmann wavefront sensor consists of a lenslet array producing 14×14 subaperatures over the pupil, and uses an OCAM2 EMCCD camera running at 1.5 kHz. Several OD6 1064 nm notch filters and a light tight box are used to eliminate any scattered 1064 nm laser light, to prevent contamination of the LGS and tip-tilt signals. Focus is removed from the DM commands and sent to the LGS facility to maintain focus on sky. An open loop control is used to focus the Shack-Hartmann on the expected LGS altitude for the current telescope elevation, and a steering mirror is used to keep the LGS on the wavefront sensor optical axis while the LGS is pointed ahead of the telescope track (Fig. 1). The point ahead angle of the LGS is determined by the current tracking velocity and the range to the Sodium layer. Photons originating from the LGS should pass through the same column of atmosphere that the infrared tracking laser will propagate to meet the target. This ensures that the tracking laser has been corrected for the atmosphere it will travel through.

Fig. 2 shows an optical schematic of the wavefront sensing sub system. All of the light collected by the telescope is passed through a beam expander and onto the deformable mirror, where the incoming and outgoing wavefronts are corrected. The incoming light in the visible is passed through a dichroic and onto the wavefront sensors. The 589 nm LGS light is directed onto the SH-WFS through the focus compensating trombone, and the remainder is passed to the tip-tilt detector. The outgoing probe laser joins the optical path at the laser dichroic and is corrected by the deformable mirror before being directed through the optical system and telescope to the target. Returning laser pulses are also reflected by this dichroic and are passed to the laser system for separation from the outgoing pulses.

The tip-tilt sensor also serves as a telescope tracking and acquisition imager. It consists of an Andor 860 EMCCD camera which images the tracked object. The tip-tilt

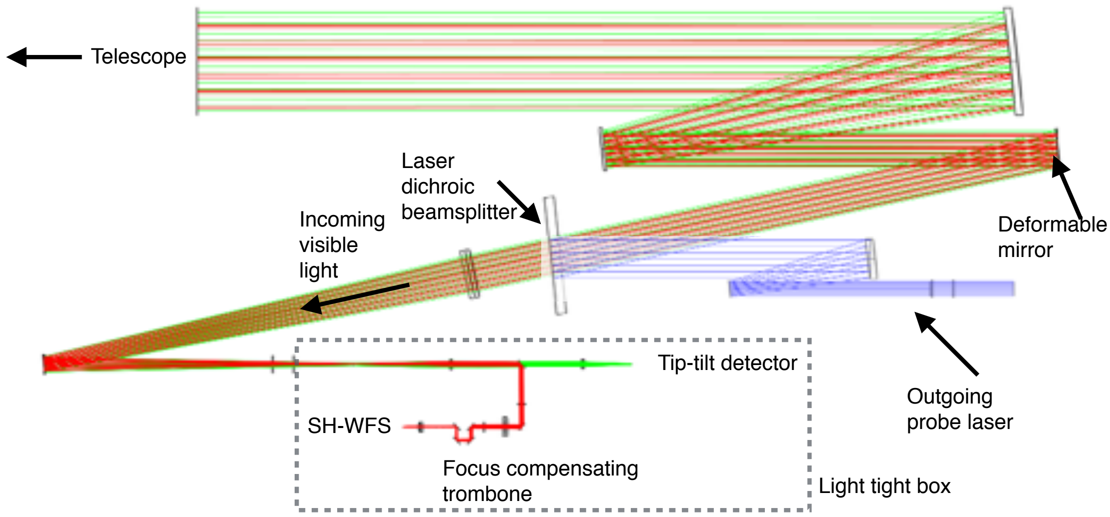

Figure 2: An optical schematic of the wavefront sensing sub system. Light from the telescope passes through a beam expander and onto the deformable mirror, and reflected to the SH-WFS and tip-tilt detector within a light tight box. The outgoing probe laser is combined to the optical path with a dichroic, and the corrected laser pulse travels back through the optical system to the telescope.

loop operates at 500 Hz and drives a tip-tilt stage on the DM.

ADAPTIVE OPTICS FOR ORBIT PERTURBATION

Active tracking technologies are always limited by the collecting area and coupled illumination power. While large telescopes and power laser systems are expensive, they may prove to be the most cost effective means of tracking orbiting objects because the technology is well developed for astronomical applications, and several ground stations could conceivably track the vast majority of hazardous debris objects. The most pressing concern currently is tracking a sufficient number orbiting objects accurately enough to predict with a high degree of certainty any possible collisions. This will greatly assist in the prevention of the Kessler syndrome of exponential growth in space debris. Further mitigation measures which may now be too expensive to consider can then be implemented to begin reducing the number of debris in orbit.

One possibility to control the growth of space debris is to capture and return larger objects such as spent rocket stages or inoperable satellites, by capturing them with another space craft[8] or satellite and placing them on a high-drag quickly decaying orbit. While this may be feasible for large space debris, the majority of debris is made up of objects < 10 cm in size. These objects would prove difficult if not impossible to remove from orbit both because of their size and number.

A leading candidate for the active management of the space environment is to use a high power ground based laser to perturb[2, 5, 9, 10, 11] the orbit of uncontrolled debris objects. This approach uses photon pressure to modify the orbit of a target to avoid a possible collision. This allows active satellites to operate for longer as their fuel load is no longer needed to dodge debris objects, and debris on debris collisions can be avoided, which reduces the overall growth in debris. As the technology matures it may be possible to manoeuvre some of the debris into specific orbits, or even deorbit objects.

Every time a photon is reflected or scattered from a surface it deposits a small amount of momentum p_{ph} to the reflecting body: $p_{ph} = h/\lambda$, where h is Plank's constant, and λ is the wavelength of light. The momentum is transferred in the direction the laser beam is reflecting from the target (Fig. 3), which can have a component along the targets orbital

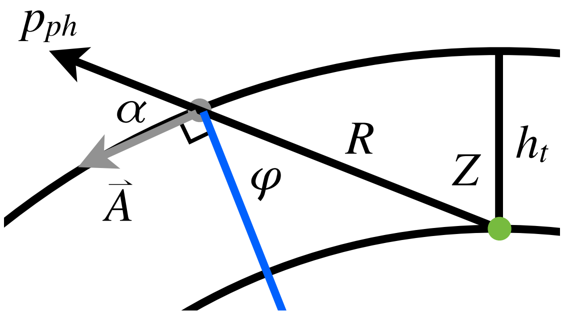

Figure 3: A schematic for photon pressure adding momentum $\vec{A}$ along the targets orbit.

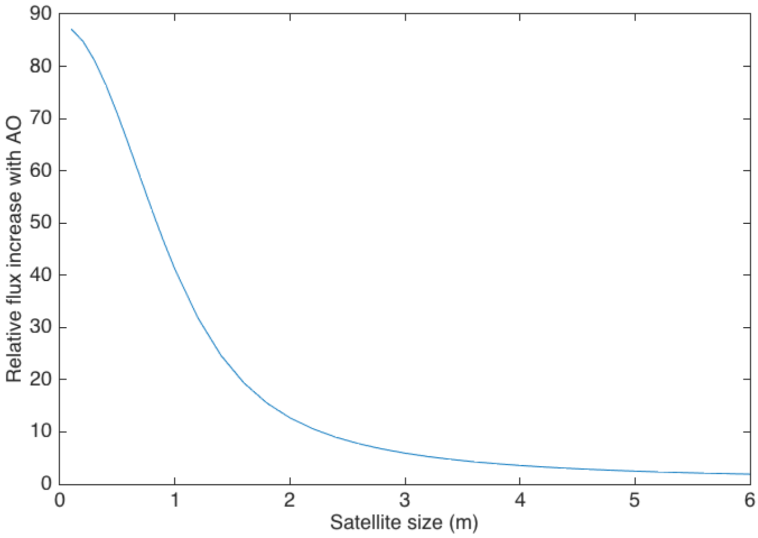

Figure 4: Relative flux increase at 800 km with an AO system on 1.8 m telescope with 1064 nm laser, vs satellite size.

velocity $\vec{A}$. By applying this photon pressure over several passes it should be possible to perturb the target's orbit by a measurable amount. On Earth these photon pressure effects are negligible due to the difference in the momentum deposited and friction caused by the atmosphere. In orbit such friction is absent, and photon pressure can be used to modify the orbit of an object. This is yet to be demonstrated because the laser power required to deposit enough momentum to modify the orbit of an object a measurable amount is prohibitively expensive that it is impractical. Even with the advances in high power infra red fibre laser capable of tens of kiloWatts of power, atmospheric turbulence still diffracts the laser beam rendering the photon density at the target too low.

Adaptive optics can be added to the system to increase the flux on the target in exactly the same way as used to increase laser ranging capabilities. AO pre compensates for atmospheric turbulence and reduces the spot size at the target. For example an AO system which can achieve a Strehl ratio of 50% at the laser wavelength of 1064 nm will provide nearly two orders of magnitude more flux on a 0.1 m target at 800 km, when compared with a natural seeing condition of 1.5 arc seconds (Fig. 4). Small targets receive the biggest flux increase from an AO system because the laser beam profile is Gaussian, with the majority of the energy concentrated in the centre.

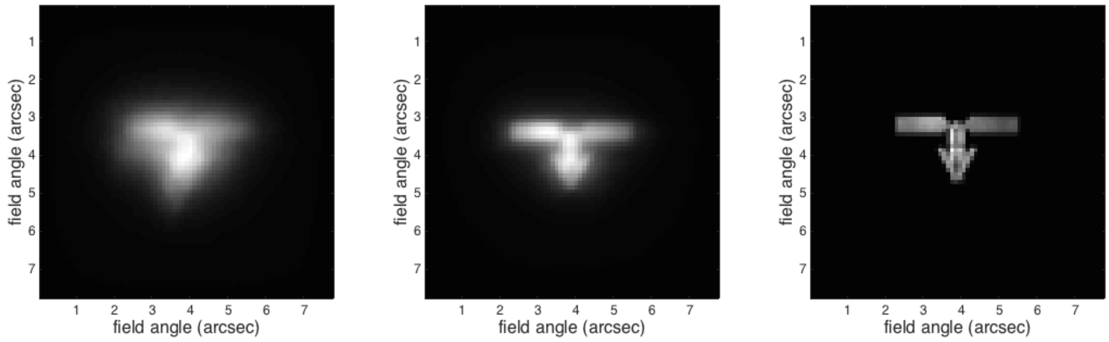

Figure 5: Iridium satellite at 800 km altitude imaged with 1.8 m telescope (left) without AO compensation, (middle) with AO compensation, and (right) original image with same pixel scale.

ADAPTIVE OPTICS FOR SATELLITE IMAGING

RSAA has been actively developing compact and high performance AO systems for satellite imaging. These AO systems share many design challenges with AO for laser ranging and orbit perturbation, due to the similar operational requirements or non-sidereal tracking. Satellite imaging requires a higher performing imaging system when compared to a laser ranging AO system. Our approach is to use a low noise high speed detector such as an EMCCD for imaging, which removes the need to correct high speed tip-tilt. Instead images can be processed in real time to remove image motion and field rotation. This removes the need for any derotating optical elements which otherwise add cost and complexity to the system.

Any system for imaging satellites must be optimised for a particular purpose, as the angular size of satellites varies widely between low altitude small satellites such as cubesats, to geosynchronous satellites which are meters in size. The telescope diameter will determine the resolving power of the system, which is used to tailor the imaging system. For example a 1.8 m telescope can resolve objects around 40-50 cm in size with wavelengths between 800 and 1000 nm for a satellite at 800 km, with an AO system. In contrast without AO the same telescope situated at Mount Stromlo would only be able to resolve features 6 m in size, under seeing conditions of 1.5 arc seconds. Fig. 5 shows simulated satellite images of an Iridium satellite at 800 km altitude without AO compensation (left), with AO compensation (middle), and the original image for comparison at the same pixel scale. The original image is a perfect image of the satellite, and so shows much finer detail than the AO compensated image. The AO compensation clearly improves the resolution, turning a fuzzy blob into a resolved object.

Resolving small features of satellites can provide new information on satellite orientation or debris tumbling which can be used to further refine orbital parameters and predictions. It would also allow the characterisation of the state of debris objects and may play an important role in space environment management by providing more information on what is currently in orbit, including providing good candidates for deorbiting experiments.

CONCLUSION

RSAA has developed AO systems for space debris ranging, debris orbit perturbation, and satellite imaging. These systems share many similarities but have been optimised for their particular application. A laser guide star and Shack-Hartmann wavefront sensor are used to measure atmospheric turbulence, which is corrected by a deformable mirror. The AO system must run at high speed to account for the high slew rates of non-sidereal tracking, and low noise high speed imaging cameras allow the system to operate without the need of a field derotator.

An AO demonstrator for ranging space debris has been designed and built, and is currently undergoing commissioning as a natural guide star AO system while the LGS system is finalised. It is expected that this AO system will achieve a Strehl ratio of over 30% at 850 nm, and increase the return photon count by an order or magnitude. This system will then be upgraded to include a high power laser to apply photon pressure to debris targets.

RSAA has also designed and built a very compact AO system to image satellites for a 1 m telescope and will be the basis of another AO system for the EOS 1.8 m telescope to image satellites and debris in both low Earth and geosynchronous orbits. We expect this system to achieve a strehl ratio of around 30% to resolve objects of less than 0.5 m at 850 nm.

These compact and high performance AO systems RSAA have been developing are using the latest technologies to improve our space situational awareness and will provide opportunities to manage the space environment. Future development of these AO systems will be in collaboration with the SERC partners with the goal of applying photon pressure to demonstrate debris orbit perturbation, and improve current tracking capabilities for objects in LEO and at geosynchronous orbits.

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