Harnessing Adaptive Optics for Space Debris Collision Mitigation

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ABSTRACT

Human kind's continued use of space depends upon minimising the build-up of debris in low Earth-orbit (LEO). Preventing collisions between satellites and debris is essential given that a single collision can generate thousands of new debris objects. However, in-orbit manoeuvring of satellites is extremely expensive and shortens their operational life. Adjusting the orbits of debris objects instead of satellites would shift the responsibility of collision avoidance away from satellite operators altogether, thereby offering a superior solution. The Research School of Astronomy and Astrophysics at the Australian National University, partnered with Electro Optic Systems (EOS) Space Systems, Lockheed Martin Corporation and the Space Environment Research Centre (SERC) Limited, are developing the Adaptive Optics Tracking and Pushing (AOTP) system. AOTP will be used to perturb the orbits of debris objects using photon pressure from a 10 kW IR laser beam launched from the 1.8 m telescope at Mount. Stromlo Observatory, Australia. Initial simulations predict that AOTP will be able to displace debris objects $\sim$10 cm in size by up to 100 m with several overhead passes. An operational demonstrator is planned for 2019. Turbulence will distort the laser beam as it propagates through the atmosphere, resulting in a lower photon flux on the target and reduced pointing accuracy. To mitigate these effects, adaptive optics (AO) will be used to apply wavefront correction to the beam prior to launch. A unique challenge in designing the AO system arises from the high slew rate needed to track objects in LEO, which in turn requires laser guide star AO for satisfactory wavefront correction. The optical design and results from simulations of estimated performance of AOTP will be presented. In particular, design considerations associated with the high-power laser will be detailed.

1 INTRODUCTION

To minimise the need for costly in-orbit manoeuvres, satellites are frequently launched into stable low Earth-orbits (LEOs) ($<$ 2000 km altitude) with lifetimes on the order of centuries. As a result, orbital debris—in the form of non-operational satellites, rocket bodies and fragments resulting from collisions—also tends to accumulate in these orbits, where it can remain a collision hazard for many years. Minimising the frequency of debris-on-debris and satellite-on-debris collisions in these popular orbits will soon become essential in avoiding Kessler syndrome, referring to a runaway cascade of collisions which produce so much debris as to render the orbital environment unusable [1]. Significant advances in space situational awareness (SSA) will be required in the next decade to secure our future use of the space environment.

The hazard posed by debris objects strongly depends upon their size. Objects larger than 10 cm are few in number and usually tracked, enabling collisions to be readily avoided by in-orbit manoeuvres, whilst protective shielding can protect satellites from impacts caused by those less than 1 cm in size. Meanwhile, debris objects between 1 cm and 10 cm in size can cause substantial damage and are difficult to track precisely. These objects therefore represent the most hazardous class of objects [2], with only 19,000 of a total estimated 600,000 objects larger than 1 cm being tracked [3]. The numbers of these objects in LEOs is of particular concern, with many objects between 400 and 900 km re-entering the Earth's atmosphere only on timescales of years, and those above 900 km essentially permanent [4].

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Given the significant cost of in-orbit manoeuvres, modifying the orbits of debris in the 1–10 cm range rather than operational satellites would be ideal in the event of a predicted collision. Various ground-based and space-based systems for debris manoeuvring have been proposed, with some of the most promising including continuous wave (CW) and pulsed laser ablation and photon pressure [4, 5]. Unfortunately, the energy requirements of the lasers needed means that space-based systems are infeasible for the time being, as they require hundreds of square metres of solar panels [3]. Moreover, space-based systems constrained to a single orbit will be limited in the range of debris objects that can be targeted, and cannot be easily maintained or refuelled. Ground-based solutions, on the other hand, generally have a much shorter time from conception to demonstration, and can be strategically placed to achieve near-full coverage of LEO orbits; however, any optical system will be limited by atmospheric turbulence.

The Adaptive Optics Tracking and Pushing (AOTP) system is a ground-based system that will demonstrate the concept of using photon pressure from a high-power (HP) 1064 nm 10 kW laser to modify the orbits of LEO debris objects over series of successive overhead passes [6, 7]. AOTP is being jointly developed by the adaptive optics (AO) group at the The Research School of Astronomy and Astrophysics (RSAA) at the Australian National University (ANU), Electro-Optic Systems (EOS) Space Systems and Lockheed Martin Corporation in partnership with the Space Environment Research Centre (SERC), which manages the Cooperative Research Centre for Space Environment Management funded in part by the Australian government. The principle aim of AOTP is to act as a demonstrator to prove the concept of ground-based orbital debris manoeuvring via photon pressure.

A challenge of designing such a system is the distortion of the laser wavefront as it is propagated through the atmosphere, resulting in a reduction of photon flux on the target. An AO system will be used to increase the on-target Strehl by pre-compensating for distortion of the laser beam before it is propagated through the atmosphere towards the target. AOTP is being developed alongside the Adaptive Optics Imaging (AOI) system, an AO-enhanced system for LEO and geostationary Earth-orbit (GEO) satellite imaging which will also be deployed on the EOS 1.8 m telescope at Mount Stromlo Observatory, Canberra, Australia. AOI may be used to identify suitable targets for engagement with AOTP; the system is detailed further in [8] and [9]. With a proven track record of delivering AO systems for SSA [8, 10], the RSAA is well-positioned for developing AOTP.

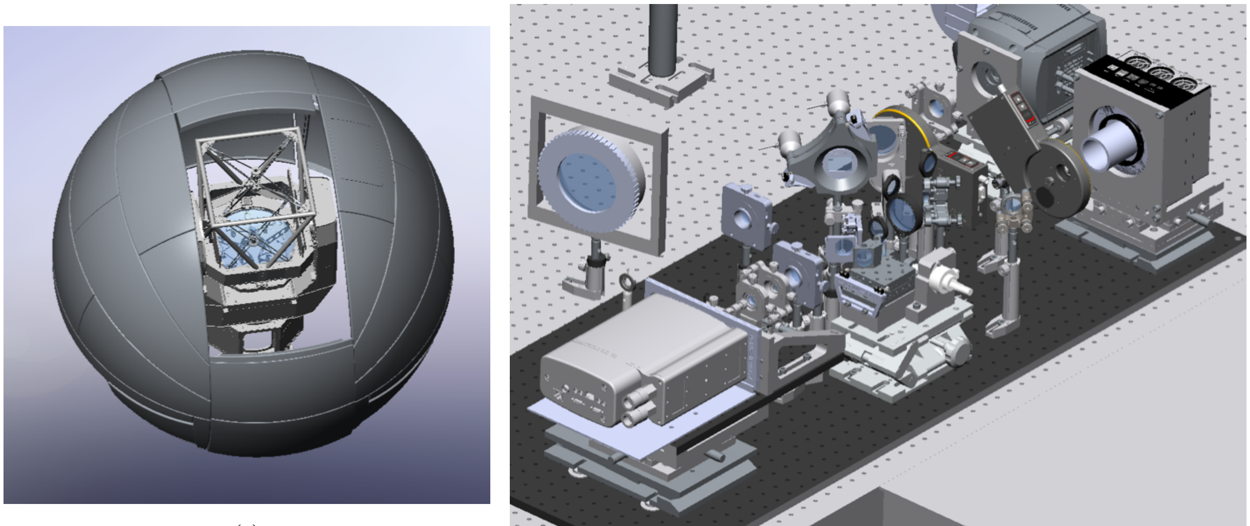
2 SYSTEM DESIGN

The AOTP system is modelled on the Adaptive Optics Demonstrator (AOD) system, an AO-enhanced system for tracking debris objects in LEO using laser ranging, also developed by the RSAA and EOS Space Systems for the EOS 1.8 m telescope. The AOD system was designed for tracking and ranging debris objects down to 1 cm in size using a pulsed 1064 nm laser with 200 W average power, using laser guide star (LGS) AO to compensate for atmospheric turbulence [6, 7, 11]. The momentum imparted to the target must at least be on the same order of magnitude as that from other external forces, such as solar radiation and other space weather phenomena, in order to be effective. As a result, manoeuvring orbital debris via photon pressure requires a far more powerful laser in comparison to one used for tracking alone. In contrast to the pulsed laser employed in AOD, AOTP will use a CW fibre laser with 10 kW power, also at 1064 nm. Migrating from a pulsed to a CW laser means that AOTP cannot be used for ranging of debris objects as there is no way of measuring the return travel time of laser light.

AOTP and AOD have nearly identical optical designs. CAD models of the telescope and optical layout of the AOD system are shown in Fig. 1, the layout of the Coudé path shown in Fig. 2 and the optical design of the AO system itself in Fig. 3.

System architecture. The physical and functional architecture of AOTP are shown in Fig. 4. The AO system works by measuring the shape that distorted wavefronts have after propagating through the turbulent atmosphere, and using this information to apply the appropriate correction to the wavefront of the HP leaser beam prior to launch. Light from the LGS is used to measure high-order (i.e. high spatial frequency) wavefront distortions, whilst reflected sunlight from the tracked target is used to measure wavefront tip and tilt. The deformable mirror (DM) and tip-tilt stage apply the corresponding wavefront correction to the HP laser beam such that the turbulent atmosphere reverts the applied perturbation, reducing distortion in the wavefront when it reaches LEO altitudes. The AO system is closed-loop, meaning that the incoming wavefronts from the object and from the LGS are measured after being corrected by the DM.

The system's specifications are given in table 1. The DM is a Xinetics lead magnesium niobate (PMN) 177-actuator model with actuators arranged in a 15×15 grid which is mounted on a tip-tilt (TT) stage. The high-order LGS WFS



(a)

(b)

Figure 1: CAD models showing (a) the EOS 1.8 m telescope and dome onto which AOTP will be deployed, and (b) the optical layout of the AOD system, the precursor to AOTP.

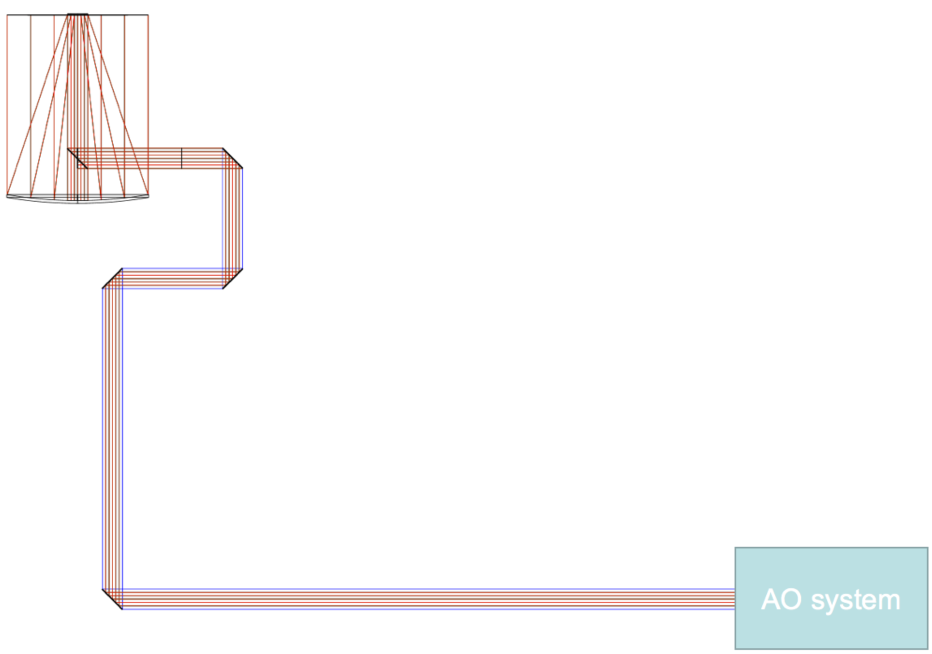
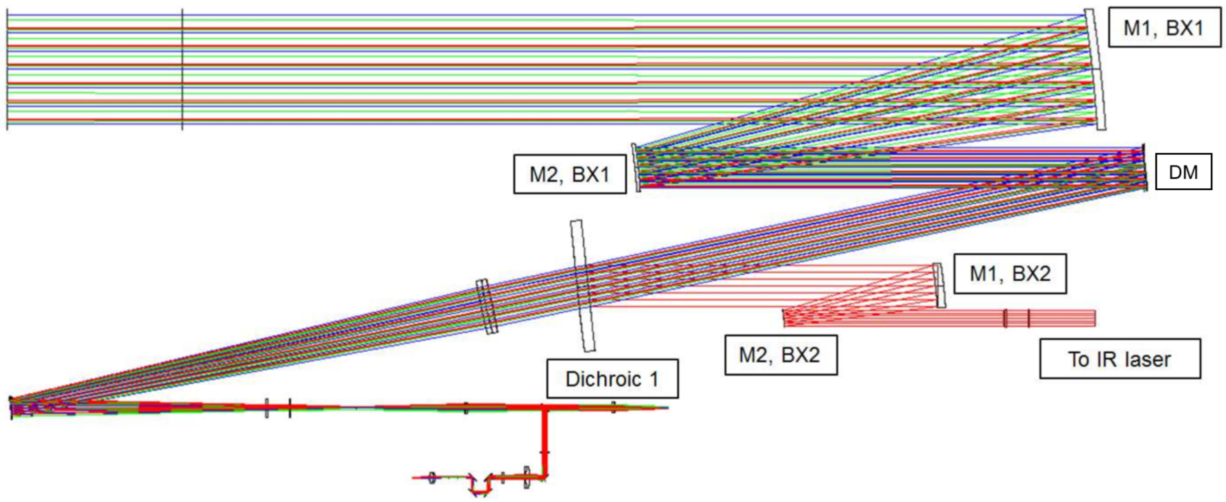
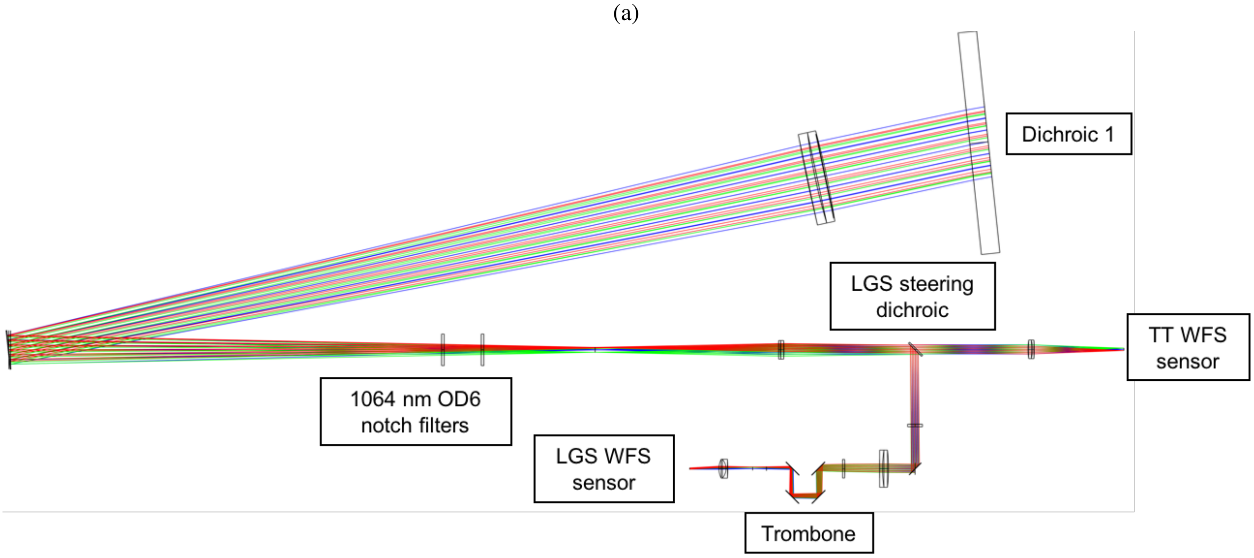


Figure 2: The Coudé path of the telescope, showing the primary mirror and the location of the AO system in the Coudé room.



(a)



(b)

Figure 3: The optical design of (a) the AO system and (b) detail showing the components in the wavefront sensing arm. Differently coloured rays correspond to different field angles. The trombone mechanism in (b) was used in the AOD system to maintain the focus of the LGS WFS on the sodium layer. Due to changes in the WFS design, it is no longer required in AOTP and will be left stationary (see Section 3).

comprises an OCAM2k electron-multiplied CCD (EMCCD) detector behind a microlens array, whilst the TT WFS, doubling as the acquisition imager, consists of an Andor 860 EMCCD detector.

Due to the non-sidereal nature of LEO targets, background stars cannot be used as natural guide stars (NGSs) for high-order wavefront sensing. Reflected sunlight from the target may be used as the NGS (which has successfully been used in AO-enhanced satellite imaging; see [8]); however the small size of suitable targets for AOTP combined with the required wavefront sensing rate of > 1 kHz disallows this due to insufficient flux, meaning that a laser guide star (LGS) must be used instead. A sodium LGS design has been chosen, in which a guide star laser (GSL) at 589 nm is used to excite atoms in the atmosphere's sodium layer at an altitude of roughly 90 km, creating an artificial star that can be used to measure wavefront distortion caused by the turbulent layers of the atmosphere. The GSL will be launched from a small refractive telescope mounted on the side of the telescope structure; the design of the GSL facility for AOTP is detailed in [11].

The HP laser is a 10 kW CW fibre laser at 1064 nm manufactured by IPG Photonics with a near-uniform beam profile. The HP laser beam propagates through the optical system on-axis whilst the incoming LGS and TT wavefronts are off-axis for reasons discussed in section 3.

Table 1: AOTP AO system parameters.

AO system parameter	**Specification**
Number of actuators	177
Number of lenslets	14×14
Pixels per subaperture	12
High-order wavefront loop rate	2 kHz
Tip and tilt wavefront loop rate	500 Hz

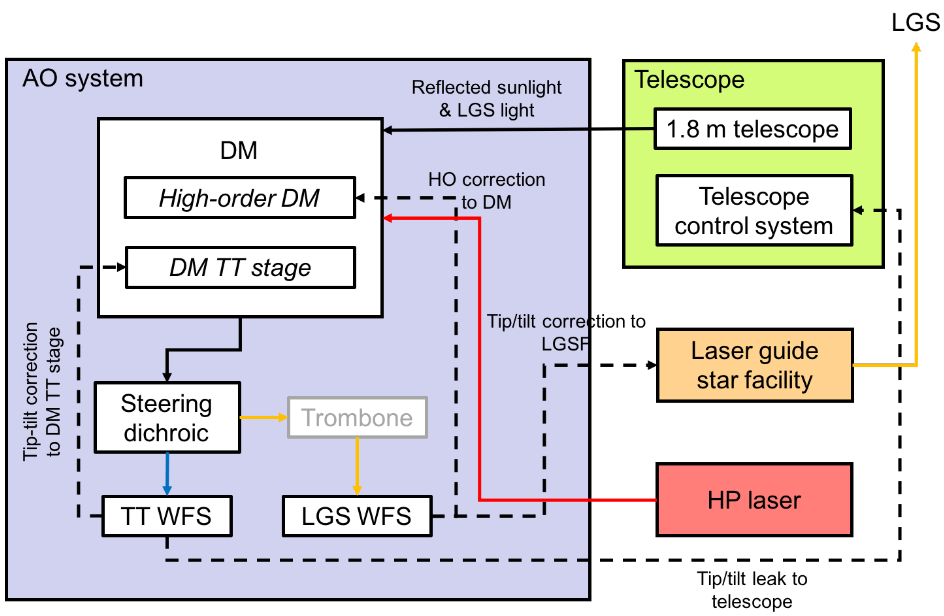


Figure 4: Schematic showing the physical and functional architecture of AOTP, with control interfaces indicated by dashed lines and optical interfaces by solid lines. Red lines denote 1064 nm laser light, yellow lines 589 nm LGS/GSL light, and blue lines reflected sunlight from the target.

AO system control. The AO system is of a single-conjugate (SC) closed-loop design with separate high- and low-order (TT) wavefront correction control loops. The control logic is summarised in Fig. 4, which shows the optical (solid lines) and control interfaces (dashed lines) between different components.

Although the LGS cannot be used to measure atmospheric tip and tilt, the LGS WFS senses tip and tilt (computed from the mean of the wavefront slopes) resulting from errors in LGS positioning, which is corrected by a fast (~ 500 Hz) steering mirror in the LGS facility. The remaining high-order components correspond to distortion caused by the atmosphere, and are corrected by the DM. Meanwhile, low-frequency tip and tilt measured by the TT WFS—corresponding to true atmospheric tip and tilt—is corrected by the TT stage whilst higher-frequency tip and tilt (> 500 Hz) are corrected by the DM. Low-frequency tip and tilt errors that cannot be compensated by the TT stage are leaked to the telescope track.

3 DESIGN CHALLENGES

The high slew rate requirement of the system and the HP laser in the optical path impose novel design challenges which are not encountered in typical AO systems.

Tracking of objects in LEO. Tracking objects in LEO requires slew rates on the order of $\sim 1°$ per second compared to ~ 15" per second for sidereal tracking. The high relative speed between the object and the atmosphere effectively increases the wind speed that is seen by the AO system, in turn placing greater demands upon the loop rate. Whilst loop rates under 1 kHz normally suffice for astronomical AO systems, AOTP will require a loop rate > 1 kHz for high-order wavefront correction and tip-tilt correction of order 500 Hz. The high-order correction rate is limited by the maximum framerate of the OCAM2k detector in the LGS WFS (2 kHz), whilst the TT correction rate is limited by that of the Andor 860 EMCCD in the TT WFS (500 Hz).

A related design complication is time-varying defocusing of the LGS as imaged on the high-order WFS due to changes in the length of the line-of-sight to the sodium layer across the track of an orbiting object. The AOD design incorporated a focus-compensating trombone (as shown in Fig. 3b) with open-loop control to keep the LGS WFS focused on the sodium layer at 90 km. However, simulations have shown that increasing the number of pixels per subaperture in the LGS WFS and performing focus compensation in software eliminates the need for the trombone whilst maintaining the necessary loop rate, simplifying the design considerably. Hence the trombone will be left stationary in AOTP.

Point-ahead. The high altitudes and speeds of LEO objects make the light travel times involved significant. As a result, the HP laser beam must be pointed slightly ahead of the true location of the target (up to 5") to ensure that the beam will intercept it. Meanwhile, the reflected sunlight from the object used to measure atmospheric tip and tilt will appear behind the target's true location. In order to apply the optimal correction to the HP laser wavefront, the wavefront measurements must also sample the atmosphere within the isoplanatic patch θ_0 of the patch of atmosphere intercepted by HP laser beam. As a result, the GSL must be pointed slightly ahead (up to 5") of the HP beam to account for the light travel time to the sodium layer. An illustration showing the different angles involved with respect to the optical axis is shown in Fig. 5

The point-ahead angle of the GSL requires incoming light from the LGS to be steered back on-axis to be measured by the LGS WFS, which is accomplished via open-loop control of the LGS steering dichroic (as indicated in Fig. 3b). Meanwhile, analogous steering of the TT wavefronts onto the TT WFS is accomplished in software. The point-ahead angles are discussed in more detail in [6, 8].

High-power laser. The presence of a 10 kW laser beam in the optical path presents a number of design challenges.

The optical design must be afocal due to hazards associated with focusing a HP beam; as a result, the DM and LGS WFS cannot be conjugated to the pupil. As a result, the footprints of the off-axis LGS and TT wavefronts do not coincide with the on-axis HP laser beam on the DM, leading to a mismatch in wavefront correction between the LGS wavefront and that of the HP beam and a reduction in the quality of AO correction. Although this could be solved by removing the point-ahead of the GSL, simulations have revealed that the performance improvements from the point-ahead outweigh losses caused by the mismatch due to improved wavefront sensing.

Another implication is that phase variations in the pupil plane correspond to amplitude variations at the DM and LGS WFS planes. The AO system in its present form is unable to compensate for the resulting amplitude losses; whether or not any associated power losses in the HP laser will be significant will be addressed in a future investigation.

An additional complication associated with the HP laser are the effects of thermal blooming, i.e. self-distortion of the laser beam caused by heating of the air through which the beam propagates. Thermal blooming may result in a

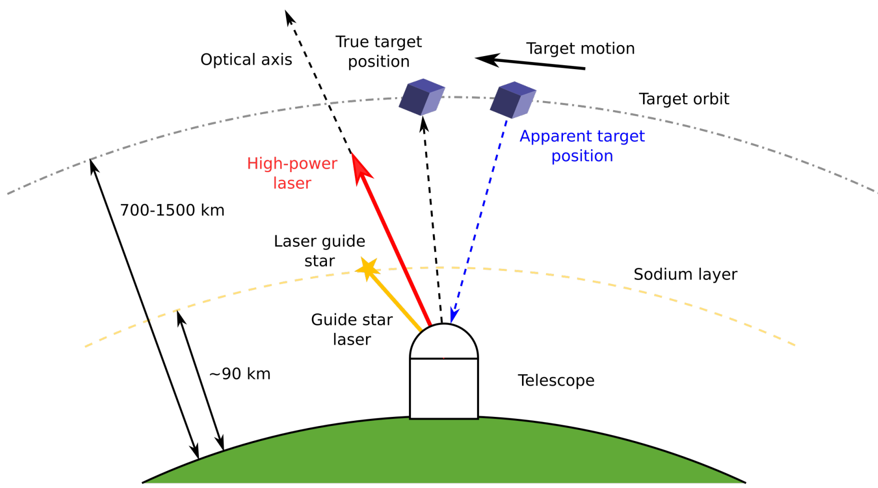


Figure 5: An illustration showing the arrangement of on- and off-axis components involved in AOTP, including the GSL, the HP laser and the reflected sunlight from the object, with the 'true' location of the debris object also shown. The HP laser beam is propagated along the optical axis of the system.

loss in on-axis intensity, defocusing and/or an asymmetric beam profile, depending on the dominating mechanism of heat transfer [12]. All of these effects will lead to a loss in Strehl, thereby lowering the on-target photon flux. Thermal blooming effects are expected to be most significant in the Coudé path (see Fig. 2) due to its length ($\sim$ 20 m) and a lack of ventilation. Modelling is being carried out to determine whether or not any changes to the design will be required.

Fast acquisition. At LEO altitudes, targets will only remain in view of the telescope for several minutes. Moreover, AOTP will be unable to engage targets with an elevation higher than 76° due to vignetting of the GSL by the telescope dome, shown in Fig. 1a. After an object passes above this elevation, the system will be unable to track it, and will have to reacquire the target after it passes through this 'keyhole', representing an additional loss in engagement time.

Before a target can be engaged, however, the AO loops must be closed. This in turn requires any differential pointing between the telescope and GSL to be compensated for, which can be achieved by scanning the GSL within a small window via a fast-steering mirror in the LGS facility (detailed in [11]) until it is acquired on the LGS WFS. Minimising this acquisition time is vital in maximising the length of the engagement period, and in turn the orbital perturbation, that can be effected.

Fig. 6 shows the sequence of steps that are required to acquire the LGS on the LGS WFS prior to tracking a target. Following system start-up and target selection, the target is located using a wide-field camera (WFC) to within its field-of-view (FoV) and the telescope track is set accordingly. The AO control loops are then closed in sequence, starting with the NGS TT loop, followed by acquisition of the LGS on the LGS WFS, after which the LGS TT loop and finally the high-order LGS WFS loop can be closed.

For typical SC LGS AO systems, it is common for this process to take longer than the entirety of the engagement window as high-speed acquisition is generally not a key design requirement. For example, manually-operated LGS AO systems typically require up to 35 minutes for acquisition; however, the fully-automated Robo-AO system has demonstrated that this process can be carried out in a mere 42 seconds if automated [13].

4 TARGETS

Suitable engagement targets will be identified from publicly available databases, and their tracks estimated using two-line elements (TLEs) and other available data. Targets that have first been characterised using the AOI system may also be selected. The range of target altitudes which can be tracked with AOTP is expected to be limited to between roughly 700 km and 1000 km. At low altitudes, the quality of the AO correction diminishes due to the effective increase in wind speed. Meanwhile, the maximum altitude is constrained by the need to maintain TT correction, which requires that reflected sunlight from the target is sufficiently bright to measure atmospheric tip and tilt with the TT WFS. The

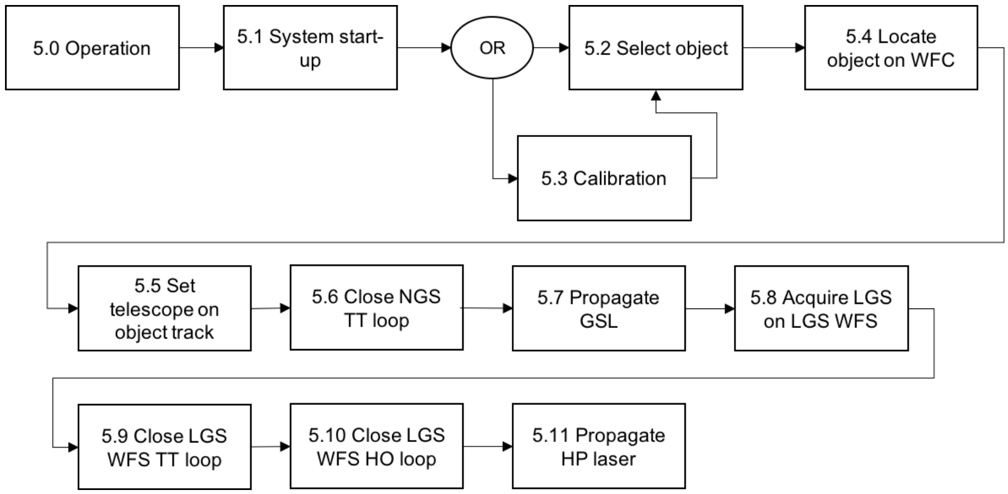


Figure 6: Flow diagram showing the sequence of operations required to acquire the LGS on the LGS WFS and to close the AO control loops prior to engagement with a target.

minimum brightness required to maintain tip and tilt correction is expected to be an I-band magnitude of roughly 14.

Accurately measuring the orbital displacement of a target before and after engagement will be vital in assessing the feasibility of AOTP for manoeuvring debris objects. Due to constraints on laser power, beam divergence, and atmospheric correction, the vast majority of target candidates will be small, uncooperative high area-to-mass ratio (HAMR) objects. Whilst these objects' orbits can be determined with traditional ground-based tracking methods such as satellite laser ranging (SLR) and RADAR, the expected perturbation effected by AOTP is expected to be within the associated error margins, as the returned flux for an uncooperative object with altitude r diminishes as r^{-4} .

A number of low-cost satellite missions may be used to enable AOTP's performance to be quantified. A first mission may involve a small satellite with on-board sensors to act as a piece of artificial debris at an altitude of 700 km. The satellite will measure the flux of 1064 nm light whilst AOTP is tracking it with and without AO correction applied, enabling the performance gains from the AO to be measured. A retroreflector will enable high-precision tracking of the satellite's altitude to measure the effected orbital displacement in collision with on-board GPS receivers and accelerometers. Such a satellite will need the appropriate attitude determination and control systems to maintain Earth-pointing of the flux sensor and retroreflector, and an end-of-life de-orbiting plan. If successful, data from the first mission may inform the design of a follow-up mission which will ideally involve multiple satellites at a range of altitudes. The satellites will be equipped with solar sails to act as HAMR objects, enabling performance models of AOTP to be verified. In particular, pairs of identical satellites in the same orbits will enable changes in orbital position caused by AOTP to be differentiated from those caused by environmental forces such as solar radiation pressure. SERC are currently in the process of assessing the feasibility of these missions.

5 CONCLUSION

The Adaptive Optics Tracking and Pushing (AOTP) system is a novel optical ground-based system which will use photon pressure from a 10 kW 1064 nm laser launched from a 1.8 m telescope at Mount Stromlo Observatory, Canberra, Australia to modify the orbits of space debris in low Earth-orbit (LEO). An adaptive optics (AO) system will be used to compensate for the decrease in on-target flux caused by atmospheric distortion. Successful demonstration of the Adaptive Optics Tracking and Pushing (AOTP) system will change the paradigm of SSA in proving the feasibility of manoeuvring orbital debris objects from the ground, shifting the responsibility of costly collision avoidance manoeuvres away from satellite operators. AOTP is currently in the preliminary design stage, with the conceptual design review having been carried out in July 2016; currently the system is planned to see first light by the end of 2019.

6 ACKNOWLEDGEMENTS

The authors acknowledge the support of the Cooperative Research Centre for Space Environment Management (SERC Limited) through the Australian Government's Cooperative Research Centre Programme.

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