ADAPTIVE OPTICS FOR SATELLITE IMAGING AND EARTH BASED SPACE DEBRIS MANOEUVRES

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ABSTRACT

Space Debris is becoming a more and more urgent issue and action needs to be taken to both actively reduce the amount of debris in space, and prevent space debris accumulation caused by collisions of existing debris. To investigate and mitigate the risk of collisions of space debris and satellites, a Cooperative Research Centre managed by the Space Environment Research Centre (SERC) has been established in Australia supported by the Australian government and national and international partners. The aim of the project is to improve orbital tracking and predictions and build an instrument to demonstrate remote manoeuvre by means of photon pressure and to perform high resolution Adaptive Optics (AO) imagery. The Research School of Astronomy and Astrophysics (RSAA) from the Australian National University (ANU) is one of the partners of the SERC collaboration and is developing AO systems for this purpose. There are currently two AO systems being developed. An adaptive optics imaging (AOI) system and an adaptive optics system for tracking and pushing (AOTP). Both systems will be operating with a laser guide star. The AOI system will image satellites and debris in lower Earth orbits providing information about the satellites' shape, attitude and position. It will also conduct astrometric measurements of geostationary satellites determining their position down a few meters. The AOTP system will target debris in lower Earth orbits and employ a 10 to 20 kW CW laser in order to push the debris with photon pressure in different orbits. Both the AOI and AOTP systems will be mounted on a 1.8 m telescope operated by another SERC partner Electro Optic Systems (EOS) on Mt Stromlo near Canberra, Australia. This paper outlines the current status of both systems and presents results of an earlier AO imaging system implemented on a 1 m telescope with which images resolving satellite features and orientation were successfully taken.

Keywords: Space Situational Awareness; Adaptive Optics; Optical Telescopes; Satellite Imaging; Earth Based Space Debris Manoeuvre.

1. INTRODUCTION

As hundreds of thousands of space debris objects are accumulating and the risk of collisions in space as predicted by Kessler [8] increases, more attention and efforts need to be brought to Space Situational Awareness. It is the aim of the Space Environment Research Centre (SERC) to create a more detailed data catalogue of satellites and space debris in order to calculate, determine and predict their positions more accurately, so that functional satellites can manoeuvre more efficiently around the debris. As those satellite manoeuvres are costly and shorten the life of satellites, SERC is also developing measures to prevent collisions by means of remote Earth based space debris manoeuvres by moving the debris object and not the satellite into unoccupied orbits. Furthermore, the expertise developed to achieve more accurate orbit determination and prediction will be applied to determine the success of the photon pressure experiment.

As a partner of SERC, the Research School of Astronomy and Astrophysics (RSAA) of the Australian National University provides Adaptive Optics (AO) expertise to help achieve these goals. With the help of data that will be collected by an AO imaging system that is currently being developed at the RSAA [3], the shape, structure and attitude of satellites will be modelled more precisely, which in turn will help to improve orbit determination and prediction. To mitigate the risk of collisions directly, an Earth based remote manoeuvre is being developed [10] that is designed to perturb orbits of space debris objects to prevent possible collisions. In order to achieve this, a high power laser aimed at the debris can be propagated through the atmosphere. As the atmosphere distorts the wavefronts, an AO system is being developed that compensates for this distortion and helps focus the laser beam onto the object in space.

We provide an overview of the AO systems that have been and are currently developed at the RSAA for these purposes. After giving a brief overview of the principle of AO in section 2, we review in section 3 the AO Satellite imaging systems for a 1 m and 1.8 m telescope both situated on Mount Stromlo, Canberra, Australia. The 1 m and 1.8 m telescope AO systems are detailed in subsec-

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tion 3.1 and subsection 3.2 respectively. Both telescopes are run by EOS Space Systems, another SERC partner. The 1.8 m telescope will also host the Earth based debris manoeuvre system that is currently being developed at the RSAA to target the debris, which is detailed in section 4.

2. ADAPTIVE OPTICS

Adaptive Optics is a technology that compensates for phase distortions of light waves in real time. Atmospheric turbulence distorts any wavefronts of light passing through Earth's atmosphere, effectively limiting the resolution of the ground-based telescope. The theoretical resolution limit of a telescope is set by diffraction and defined by the ratio of wavelength λ to telescope diameter D, λ/D. The resolution that is achievable in practice without the application of an AO system is however given by the atmospheric seeing above the telescope and is defined by λ/r_0, which takes the optical coherence length, also called Fried parameter r_0 into account. This parameter provides a measure for the atmosphere to maintain a constant refractive index over a certain distance and usually takes values between 5 to 20 cm in the visible for poor or good sites respectively. This means however that telescopes that are significantly larger in diameter than r_0 will always be affected by the seeing. An AO instrument is capable of correcting for these distortions and of restoring the resolution close to the diffraction limited value of the telescope.

The AO instrument receives the distorted light that propagated through the atmosphere and compensates for the distortions so that high resolution measurements can be recorded. Figure 1 details the AO operational principle. The light collected by the telescope is sent via a deformable mirror that corrects for the distortions to a wavefront sensor. The wavefront sensor measures the error of this correction and sends it to the control computer, where it is transformed into deformable mirror commands and sent to the deformable mirror, thats compensates for it again. The corrected wavefront is sent to the high-resolution camera recording the corrected and improved images for the scientific purpose. As the atmosphere is constantly changing, the system needs to be running in real time, usually at several hundred Hz. Many reference books, such as [1, 7, 9], explore the operational principle and design of AO systems with a wide range of applications in astronomy in more detail. The application of AO systems for satellite imaging and space debris manoeuvres distinguishes itself from astronomical applications in particular by its requirement of being able to compensate for atmospheric turbulence despite of the fast movement of the telescope's field of view through the atmosphere. The following section focuses on the system specifications of the AO systems for satellite imaging and provides an overview of the AO systems that are being developed in this field with the RSAA.

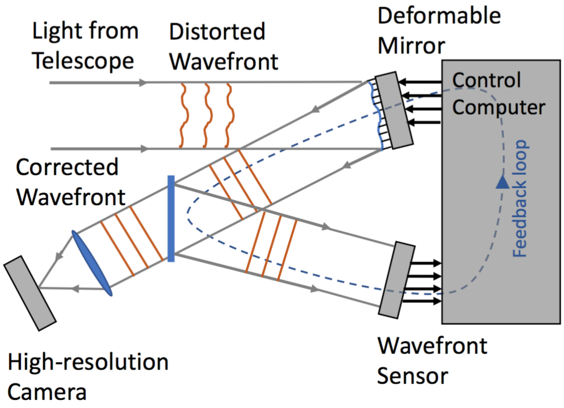

Figure 1. Operational principle of Adaptive Optics: the distorted wavefront is corrected by the deformable mirror and the residual error is measured by the wavefront sensor. The measurement is translated into further correction commands to the deformable mirror by the control computer. The corrected wavefront is sent via a beamsplitter to the science camera.

3. SATELLITE IMAGING WITH ADAPTIVE OPTICS

Optical telescopes can be used to precisely track satellites and space debris and determine their position with satellite laser ranging [4, 6]. They can also be used for imaging satellites, but the resolution of features is seeing limited unless it is compensated for with the help of an Adaptive Optics System. To help characterise satellites in lower Earth orbit (LEO), the RSAA is developing Adaptive Optics Imaging Systems.

As satellites are fast moving objects in the night sky, the AO system has special design requirements that are detailed in the following two sections. Section 3.1 provides an overview and shows results of an existing satellite imaging system designed to image satellites in LEO with a 1 m telescope [2], section 3.2 provides an overview of a satellite imaging system designed to image satellites with a 1.8 m and to support astrometric measurements of satellite positioning in Geostationary orbit (GEO) [3].

3.1. Adaptive Optics Satellite Imaging System for a 1 m Telescope

The Adaptive Optics imaging system that was developed for imaging of satellites in LEO can achieve a Strehl ratio of 20% at an altitude of 1000 km, but can also perform in lower altitudes down to 600 km. The system is depicted in Figure 2. It uses the reflected sunlight from the satellites in the visible as natural guide star light for the wavefront sensor and the infrared part for imaging. The entire light collected by the telescope is reflected via a beam expander and scaled down to suit 1'⌀optics. The light is reflected off the deformable mirror to a dichroic beam splitter that lets light below 800 nm pass to the wavefront

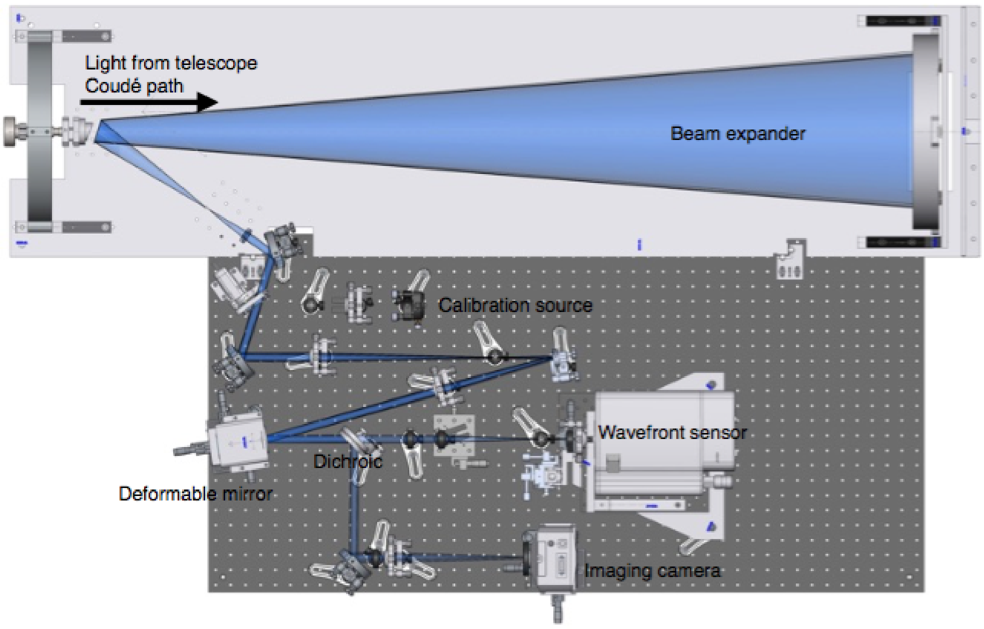

Figure 2. Design of the AO imaging system for a 1 m. telescope. The light from the telescope is scaled down, reflects off the deformable mirror and is spectrally split by a dichroic beam splitter to the wavefront sensor and the imaging camera.

sensor. Light above 800 nm is reflected off the dichroic and onto the imaging camera that uses light between 800 and 950 nm. A light from a calibration source can be inserted to calibrate the setup and register the deformable mirror to the wavefront sensor. The system runs at an AO loop rate of 2 kHz to accomodate for the fast on-sky movement of the satellite and the hence fast moving atmosphere and uses a Shack-Hartman wavefront sensor. Derotation of the image while being followed on sky is implemented in software post processing of the imaging data so that derotating optics are not necessary.

The system has a diffraction limited resolution of 0.18 arcseconds at 850 nm and is designed to image satellites in good seeing with an r_0 of about 12 - 15 cm, but can still perform at worse seeing conditions down to an r_0 of 8.7 cm for 850 nm.

Figures 3 and 4 show some of the on sky results obtained during the system's operation. First the system was tested on stellar objects. Figure 3(a) shows the image of a binary star with the AO loop closed and its close up (Figure 3(b)). Figure 4 shows several images taken of satellite Resurs-DK1 over a 30 second period. The field rotation has already been removed in software and Lucky Imaging techniques were applied to shift and stack the images of high quality. The solar panels to either side of the satellite can be seen with the body of the satellite in the middle.

A second AO system that is designed for a 1.8 m telescope is currently also being developed and is detailed in the following section.

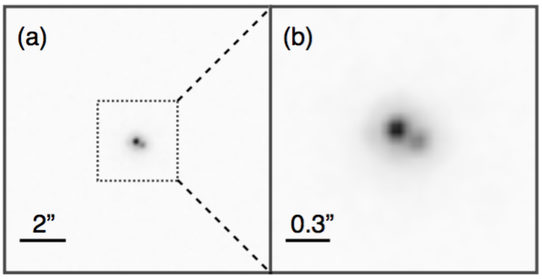

Figure 3. (a) Image of a binary star with a separation of 0.3 arcseconds and (b) the close up that shows the two stars resolved with a FWHM of 0.25 arcseconds. [2]

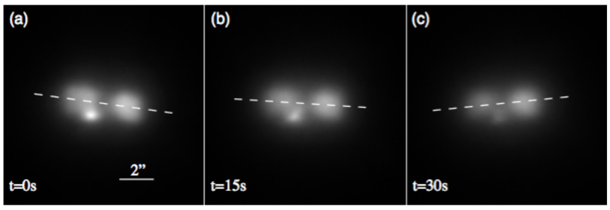

Figure 4. Image of satellite Resurs-DK1 at time (a) t=0 s, (b) t=15 s, and (c) t=30 s. [2]

3.2. Adaptive Optics Satellite Imaging System for a 1.8 m Telescope

The Design of the Adaptive Optics Imaging system, called AOI, is similar to the previously developed AO system for the 1 m telescope (see section 3.1). It is also designed to image and characterise satellites in LEO,

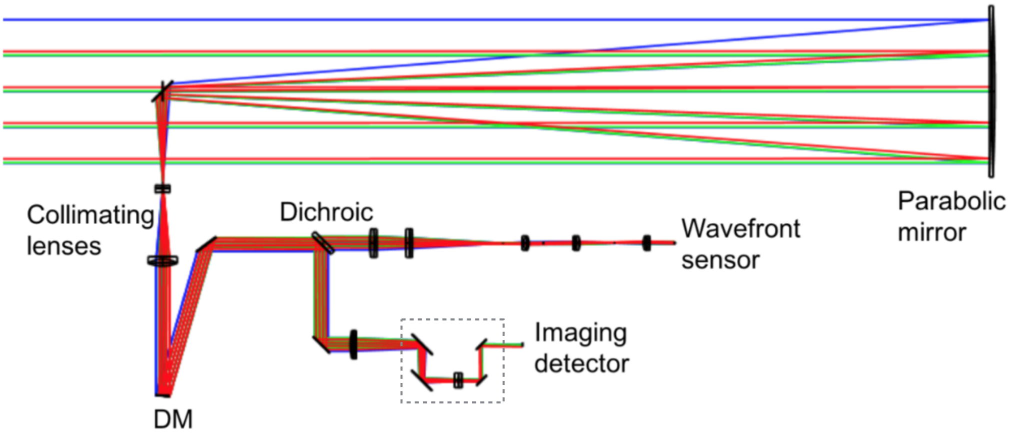

Figure 5. Optical design of the AOI imaging system. Light from the telescope sent via a parabolic mirror and two collimating lenses to the deformable mirror from where it is reflected to a dichroic, where it is split and parts of the light transmitted to the wavefront sensor and the other part reflected to the imaging detector.

however, due to its application on a 1.8 m telescope, AOI is doubling its diffraction limited resolution to 0.09 arcseconds at an imaging wavelength of 800 nm. It is also designed to accomodate for natural guide star mode using the reflected sunlight from the satellite as well as laser guide star mode for using a laser guide star also currently being developed at the RSAA [5]. Its design is shown in Figure 5.

The light from the telescope is scaled down in diameter by a parabolic mirror and two collimating lenses, before it is reflected of the deformable mirror (DM). In case of natural guide star mode, a dichroic beamsplitter transmits the light between 450 and 800 nm to the wavefront sensor and reflects light between 800 and 1000 nm to the imaging detector. In case of laser guide star mode, only light around 589 nm, which is the emitted light of a sodium guide star laser, is transmitted to the wavefront sensor and light between 600 and 1000 nm is reflected to the imaging detector.

The wavefront sensor is a Shack-Hartman wavefront sensor and is optically conjugate to the DM using a lenslet array with 16x16 subapertures and a pitch of 300 μm. The wavefront sensor camera is also an Ocam2k EMCCD, which runs at 2 kHz.

The AOI system also features a wide-field acquisition mode using a set of replaceable optics that are mounted on a motorised translation stage to increase the field of view. This stage is initially moved out of the optical path to increase the field of view of the imaging system, so that it is easier to acquire the image. Once the image is acquired, the stage is moved back into the optical path reducing the detector's field of view, but increasing its plate scale to 0.044 arcsecond per pixel to be able to Nyquist sample the diffraction limited image with an achievable diffraction limited resolution of 0.09 arcseconds. With this design, the system will be able to resolve features of 50 cm at 800 km altitude with an imaging wavelength of 800 nm.

AOI is also designed to assist in orbit determination for satellites in GEO by imaging geostationary satellites and determining their angular position with regards to catalogued stars from the Gaia catalogue. The operational concept of this astrometric measurement technique is shown in Figure 6.

When a satellite travels within 15 arcseconds separation past a star that is catalogued in the Gaia catalogue, the satellite can be imaged during its flyby and its position can be more accurately determined, by calculating the centroids of the satellite and the star image. The system is planned to go on sky in natural guide star mode in late 2017.

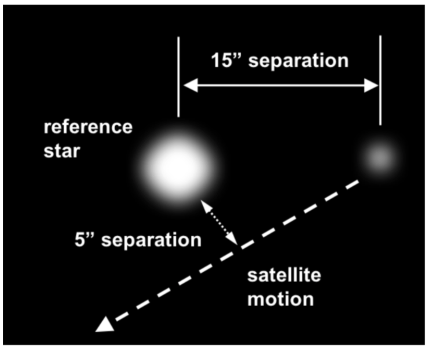

Figure 6. Diagram of satellite imaging in GEO with astrometric positioning

As shown, Adaptive optics can be used to support space situational awareness by characterising the satellites' shape and attitude and position, which can be used to improve models for orbit determination and prediction. The next step is to actively prevent collisions, which is currently done by moving the satellite out of harm's way. This is however costly and fuel inefficient and decreases the life time of the satellite. The threatening debris could be moved instead, saving fuel and expanding the life time of the satellite. The next sections provides an overview of an Earth based Adaptive Optics system, that is being designed to manoeuvre debris.

4. DEBRIS MANOEUVRE WITH ADAPTIVE OPTICS

Satellite imaging and characterisation with Adaptive Optics helps predicting collisions, but does not prevent them. In case of a threatening collision one of the objects needs to move out of the way. That is why we are developing a system to demonstrate the perturbation of an object's orbit in LEO using a ground based AO corrected laser and photon pressure [10]. As it is an Adaptive Optics system that is designed to track a satellite object and push it at the same time, it is called, Adaptive Optics Tracking and Pushing (AOTP) system. The operational principle is shown in Figure 7. A target object is acquired and tracked, before a guide star laser is propagated, creating a laser guide star to measure the atmospheric distortions with the help of an Adaptive Optics system situated behind the telescope. Once the atmospheric distortions are measured, a high power laser (HPL) is aimed ahead of the target while its beam is pre-compensated for the distortions in the atmosphere. That way, the beam can be focused onto the object in space ensuring sufficient flux density to perturb a high area to mass ratio object by means of photon pressure created with the high power laser.

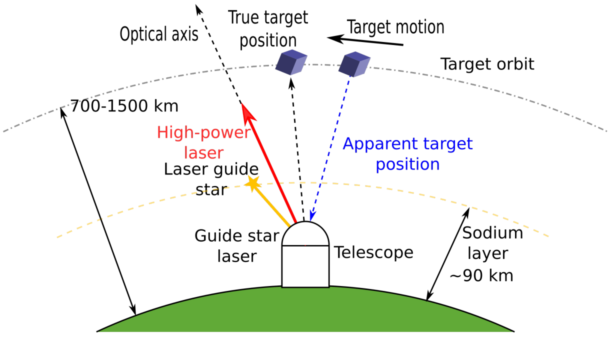

Figure 7. Debris manoeuvre operational principle: laser guide star for wavefront sensor measurements and high power laser for debris pushing manoeuvre are pointing ahead of the target to compensate for time of flight of the light [10]

The aim of the demonstration is to move an object sufficiently from the time a collision warning occurs to the time of a possible collision, which is currently two days prior to the possible collision. The time the HPL can be engaged is restricted by the limited amount of time given by the orbit, the time it takes to acquire the target and close the AO loops and the limited time the optics can be exposed to the HPL density. A HPL engagement of several passes of the object is therefore feasible.

The optical design of the AOPT system is detailed in Figure 8. The natural guide star light and the laser guide star light are fed through the Coudé path of the telescope and are fed into the optical setup via the two mirrors M1 and M2. The light gets reflected off the deformable mirror (DM) and passes through the high-power laser (HPL) dichroic. The HPL dichroic reflects light above 950 nm and lets light below 850 nm pass. The light passes through two relay lenses L1 and L2 before the light from the laser guide star (40 nm bandstop around 589 nm) is reflected by a dichroic beam splitter and send to a Shack-Hartman wavefront sensor via three relay lenses. Light below and above that bandstop is transmitted to the tip-tilt detector. The LGS dichroic is capable of adjusting the optical axis of the LGS light to the wavefront sensor as this optical axis is pointed ahead of the telescope axis. The outgoing HPL light enters the setup at the HPL dichroic and is reflected by it passing the DM and the beam expander M1 and M2 on its way to the telescope.

The wavefront sensor measures the wavefront aberrations with the LGS light and corrects for them in realtime. Hence a fast detector is needed. The Ocam2k EMCCD is chosen as wavefront sensor detector, because it runs at 2 kHz and the AO loop can be operated at this speed. Due to budget restrictions, both the AOI setup from the previous section and the AOTP setup are using the same detector for wavefront sensing. Furthermore to accomodate easy exchange, the optical design has been adjusted, so that the Shack-Hartman wavefront sensor design of the AOPT system has the same amount of subapertures on the lenslet array and the same pitch as the AOI system.

Furthermore, a special mechanical design has been developed to allow for easy switching and adjustment between the two setups. Although each setup needs to be recalibrated after replacing the detector, sharing the detector is still possible as it is relatively easy to align. Figure 9 depicts the mechanical wavefront sensor design. A kinematic mount allows for fast switching, but also adjustments in all directions as well as angular rotation of the detector if needed.

With the majority of the optical and mechanical design of the AOTP setup done, the system's software needs to be further developed. Preliminary tests of the system without the laser guide star and the high power laser system are planned for the end of 2017.

5. CONCLUSION

We have built an Adaptive Optics system for satellite imaging in LEO that uses the reflected sunlight form the satellite itself to measure and compensate for wavefront aberration improving the seeing limited resolution. The system has been tested on sky at Mt Stromlo and has resolved satellites in orbit with a 1 m telescope. As a partner of the Space Environment Research Centre, we are developing another satellite imaging system further to work in both natural and laser guide star mode, speed up the object acquisition procedure and allow the system to run in imaging mode for GEO satellites to determine their positions more accurately with the help of simultaneously taken astrometric measurements. The system is planned to be built in 2017 and tests are planned for the end of 2017 in natural guide star mode. Furthermore, we are developing an Adaptive Optics tracking and pushing system to perturb the orbit of an object in space that is threatening to collide with a functional satellite. A high power laser will be preconditioned with the help of the Adaptive Optics system to compensate for distortions cause by

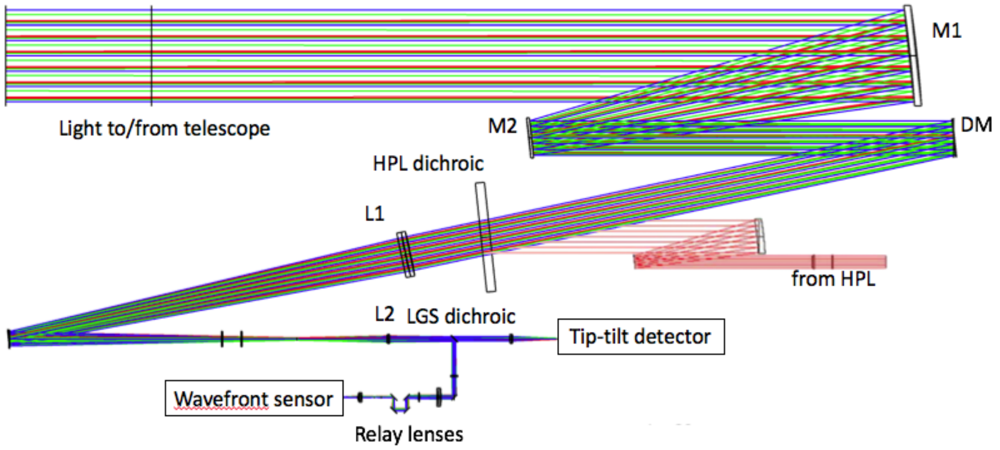

Figure 8. Optical design of the AOTP system, the NGS and LGS light is sent via the off-axis beam expander M1 and M2 via the DM and the HPL dichroic through a relay L1 and L2 to another dichroic that reflects light of the LGS around 589 nm towards the wavefront sensor and transmits the remaining visible and infrared light to the tip-tilt detector.

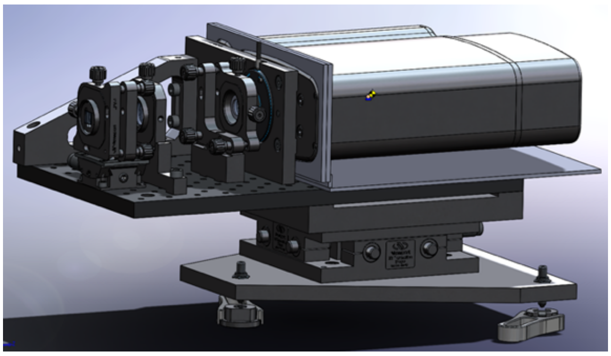

Figure 9. Mechanical design of the Shack-Hartman wavefront sensor

the atmosphere during laser propagation. The system is planned to undergo software testing in 2017 awaiting the completion of the laser guide star and high power laser system for a photon pressure demonstration in 2019.

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