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ABSTRACT

We describe the work that has gone into taking the sodium Laser Guide Star (LGS) program on the Palomar AO system from a successful experiment to a facility instrument. In particular, we describe the operation of the system, the BTO (beam transfer optics) system which controls the path of the laser in the dome, the aircraft safety systems and the optical systems which allow us to take advantage of the unique properties of the macro/micro pulse laser. In addition we present on sky performance results that demonstrate K-band Strehl ratios of up to 48%

Keywords: AO, LGS, Palomar

1. INTRODUCTION

The Palomar Adaptive Optics system has been in operation on the Hale 200" telescope for 9 years[1]. The goal of the Palomar AO LGS system was to develop a sodium laser guide star system to extend the sky coverage of the 241-actuator natural guide star AO system and to explore the benefits of using a pulsed laser for LGS work. Design decisions made based on the type of laser, the available space on the telescope, the existing AO system design and the size of the telescope led to several unique aspects of this system which are described here.

2. SYSTEM OPERATIONS

2.1 AO System Operational Modes and Servo Loops

The AO system is comprised of several major components: a 16x16 subaperture Shack-Hartmann high-order wavefront sensor (HOWFS); a 3x3 subaperture Shack-Hartmann low-order wavefront sensor (LOWFS); a 241-active-actuator deformable mirror (DM); a fast tip/tilt mirror in the AO system (TTM) and an uplink tip/tilt mirror (UTT) for fast tip/tilt steering of the projected guide star laser. The HOWFS is on a focus stage that allows correction for the changing height of the sodium layer.

Together these components can operate five possible servo loops: high- and low-order natural guide star (NGS) loops, high- and low-order LGS loops and the LGS focus loop. Tip/tilt and focus are always offloaded from the TTM and DM positions to the telescope during normal operation. In addition, during LGS operation, a focus correction for the height of the sodium layer is applied indirectly by moving the HOWFS. This causes focus to appear in the residual measurements which, in closed-loop operation, is applied to the DM. For sufficiently large offsets, focus is offloaded to the telescope secondary position. This scheme allowed the addition of a focus control loop with no alterations to the existing closed-loop operation. UTT positions cannot be offloaded, so the mirror was selected to have sufficient angular range to both steer the laser around the sky and account for turbulence-induced tip/tilt in the outgoing laser beam.

There are three operating modes for the AO system which allow mode-specific parameters to be set for closed-loop operation and acquisition. In NGS mode, the system operates as a standard astronomical AO system. The residual wavefront errors measured by the HOWFS drive both the TTM servo loop and the DM servo loop. In LGS mode, the HOWFS sees light from the laser guide star, so the residual wavefront errors it measures drive the DM servo loop and the UTT servo loop that stabilizes the laser on the sky. The LOWFS measures residual wavefront error from a natural

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guide star and uses this information to drive the TTM servo loop, as well as the HOWFS focus stage servo loop. In Dual NGS (DNGS) mode, both the HOWFS and LOWFS measure residual wavefront error from NGS. The HOWFS residuals drive the DM servo loop and the LOWFS residuals drive the TTM servo loop. In this case, the focus stage loop and UTT loop are not required. This mode is intended mostly for testing purposes.

2.2 Guide Star Acquisition

Basic NGS acquisition for the HOWFS is done manually using the acquisition camera, telescope pointing control and a pair of periscopic steering mirrors in the AO system (SSMs). The small (<3”), on-axis field required for the HOWFS is reflected off a mirrored spot into the HOWFS, while the remaining 120”-diameter field passes through to the acquisition camera. The steering mirrors allow the image and pupil to be independently aligned to the HOWFS.

For on-axis tip/tilt stars, the visible light used for both the HOWFS and the LOWFS must be split such that all the 589nm laser return is sent to the HOWFS and all the remaining visible light is sent to the LOWFS. This is implemented using a 589nm narrow-band reflector which covers the entire field. This allows all the visible light except a narrow region around 589nm to pass through and be available to the LOWFS over the full field of the system. It has the added benefit of blocking Rayleigh and other laser scatter from the LOWFS.

However, this reflector will not work for NGS operation and does not pass any of the 589nm light needed to acquire the LGS through to the acquisition camera. Having both the 589nm optic and the NGS reflecting optic available solves both of these problems. Both optics are installed on a motorized stage that is controlled through the AO system, so that the optics can be switched quickly (Figure 1). Initial LGS acquisition is the same as standard NGS acquisition. Then the optic is switched to the 589nm reflector and the NGS tip/tilt star is acquired in the LOWFS.

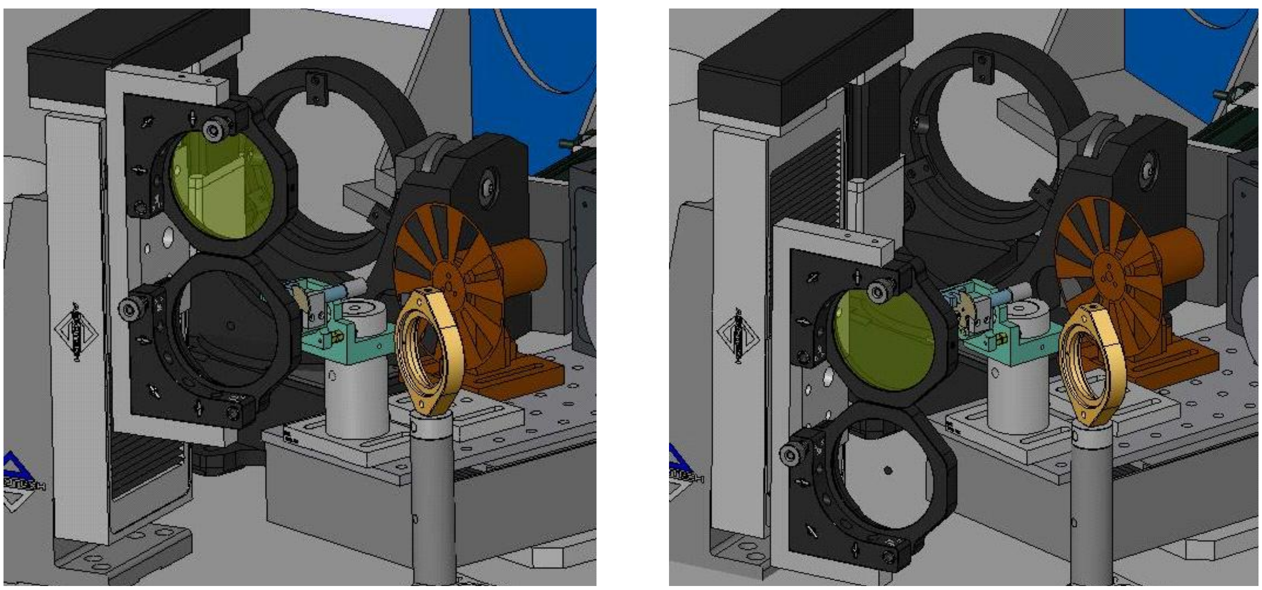

Figure 1 The figure on the left shows the reflecting spot setup. The figure on the right shows the 589nm reflector setup.

The LOWFS and the acquisition camera both need access to the full field, but not simultaneously. The LOWFS also needs to be able to be repositioned anywhere in the field in order to acquire off-axis tip/tilt stars. The LOWFS initially was mounted to a pair of 2 inch travel stages in order to cover the full field. The field access issues were resolved by replacing one of the LOWFS stages with a 4inch-travel stage. This gives enough travel to cover the field (2 inches) with sufficient travel left over to move the LOWFS out of the field and allow access to the acquisition camera (Figure 2). Because this does not allow for the manual acquisition of stars in the LOWFS, we use a calibrated mapping between acquisition camera pixels and LOWFS stage positions to send the LOWFS to the correct location to see the star.

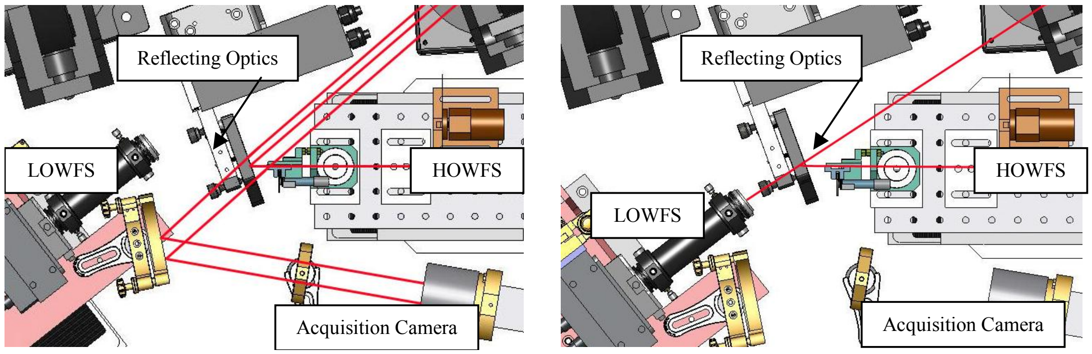

Figure 2 The figure on the left shows the beam path for HOWFS acquisition. The figure on the right shows the beam path for on-axis tip/tilt star LGS operation.

2.3 System Setup and Recovery

The LGS system takes approximately 45 minutes to check out on the sky at the start of the first night of a run and approximately 30 minutes on subsequent nights. This involves checking the focus of the laser launch telescope and of the laser itself on the sodium layer and acquiring an initial target to optimize system performance. Per target, the average acquisition time from the start of the telescope slew to the beginning of science imaging has been 16 minutes. Faint tip/tilt stars take longer to acquire because they require longer integration in the acquisition camera. The acquisition time is reduced by efficient observing software and detailed procedures. The acquisition process can be accomplished using a few automated routines to set up the stages for each operation, take backgrounds, move the LOWFS to a point in the field and center the LOWFS stages on the star.

The system recovers very rapidly after a closure from the safety system (see section 5). When there is a closure, the laser shutter is engaged, but the laser remains powered up and lasing. The LOWFS remains locked on the tip/tilt star. The science camera can continue to take data, but there is only tip/tilt correction. Once the closure event has passed and the safety systems are all clear, the laser shutter is opened. Since nothing in the laser path has changed, the sodium return is immediately visible on the HOWFS and the servo loop can be locked. It takes only a few seconds from the time the shutter is opened to return to taking science data with full AO correction.

2.4 Wavefront Sensor Range Gating

The laser used in the Palomar LGS system is the Chicago Sum-Frequency Laser built at University of Chicago by Ed Kibblewhite and Viswa Velur[2]. It is a 589nm macropulse/micropulse, mode-locked sum-frequency laser with a bandwidth of 1 GHz and an average output power of 7 W.

Unlike all other operating sodium LGS AO systems, the pulse format of the laser provides the ability to gate Rayleigh and other scattered light from the wavefront sensor. Rayleigh scatter comes from lower altitudes and thus returns more quickly than the light from the sodium layer. With this pulse format, all the Rayleigh scatter created by a pulse returns to the ground before the first sodium return. Figure 3 assumes a 180 μs macropulse every 2 ms composed of multiple 2 μs micropulses, return from the sodium layer located between 80 and 105 km above the ground and a Rayleigh scatter zone upper limit of 25 km.

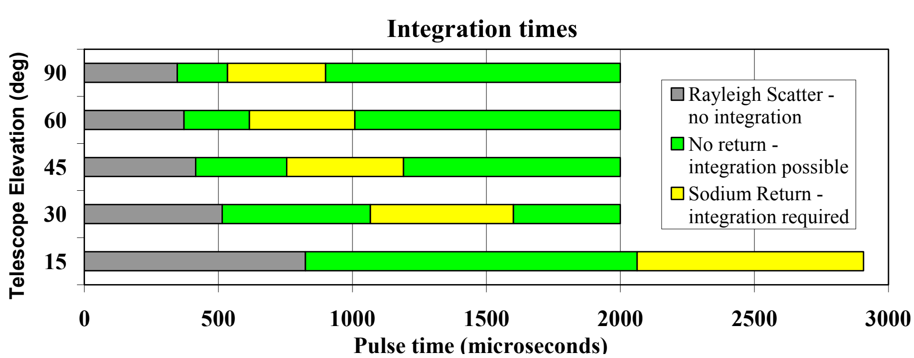

Figure 3 Laser return timing for various telescope elevations. 90 degrees is zenith

The Palomar system has two possible methods to range gate the wavefront sensor: electronic and mechanical. The electronic method synchronizes the HOWFS camera with the laser pulses to use the light from one pulse per camera frame. This method only operates at the laser repetition rate, so for improved signal to noise, the system also has an optical chopper synchronized to the laser. The chopper allows integration over multiple pulses using only the sodium return. With our current laser return and spot size, the best balance between signal to noise and HOWFS frame rate is achieved when using the chopper to gate the Rayleigh scatter. Figure 4 shows the significant impact the range gating has on LGS wavefront sensing.

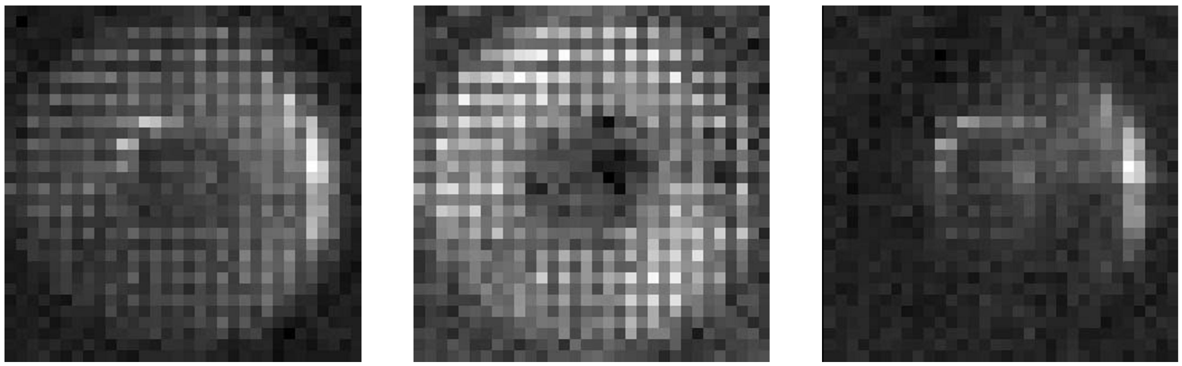

Figure 4 HOWFS frames showing the total laser return, the gated laser return and the difference between the two frames.

Because the range gating blocks all the laser light except for a small window of time for the expected sodium return, it also allows for LGS operation through thin clouds. The laser light scattered off thin clouds can be clearly seen in the acquisition camera (Figure 5), but this is gated out of the HOWFS and does not affect the closed loop AO operation.

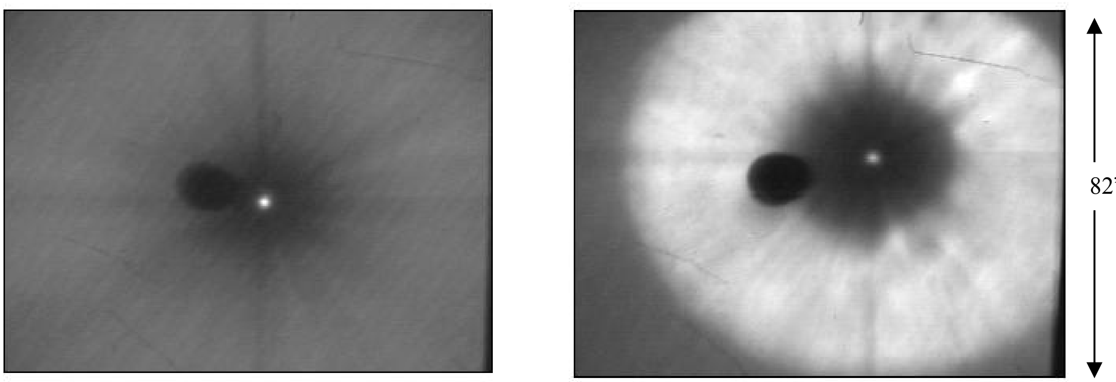

Figure 5 Acquisition images showing the sodium laser return spot and the Rayleigh scatter on a clear night and a cloudy night. The black spot is the NGS reflecting spot.

3. SYSTEM PERFORMANCE

The performance of the Palomar LGS AO system is limited both by high order error due to the limited brightness of the laser guidestar, and by low-order error dependent on the magnitude of the natural guidestar used to sense tip, tilt, and focus.

3.1 Laser Return

The system performance with natural tip/tilt guidestars brighter than V~12 is limited by the LGS magnitude. Figure 6 shows the LGS return efficiency (photons cm^{-2} sec^{-1} per Watt of laser power reaching the Na layer) as a function of date. Although we have less than two years of data to draw on, there appears to be a strong seasonality in the sodium guidestar return, with a peak in November and minimum in May. The wavefront quality delivered to the science instrument when using bright tip/tilt stars has varied accordingly, from as high as 48% K Strehl during times of abundant sodium, to ~25% K Strehl during the minima.

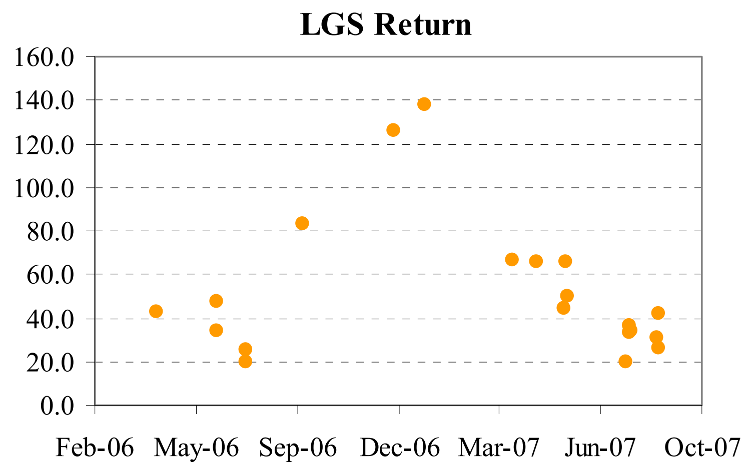

Figure 6 Laser guidestar return as a function of date, in photons cm^{-2} s^{-1} W^{-1} at the top of the atmosphere, for laser power givens in Watts reaching the sodium layer.

3.2 LOWFS Performance

The Low Order Wavefront Sensor (LOWFS) is a 3x3 Shack-Hartmann wavefront sensor that is used to measure tip, tilt and focus from a natural guide star. The performance of this sensor determines the total sky coverage available to the system. It uses a Scimeasure camera with an E2V CCD39[3]. Each subaperture consists of 6x6 pixels binned down to 2x2 to be used as a quadcell. For the binned pixels at a framerate of 50Hz, it has a measured dark current of 5.4e^- and a measured read noise of 5e^-. Like the HOWFS, it has a maximum framerate of 2000Hz.

The LOWFS can lock on a tip/tilt star that is as much as 60 arcseconds away from the laser target. This limit is imposed by the FOV of the AO system relay optics. To access this field, the LOWFS is on a motorized x-y stage.

The LOWFS can sense tip/tilt stars as low as 17.5 visible magnitude. Figure 7 shows a sample of measured K-band Strehl ratios by tip/tilt star magnitude. V=10-11 stars are used for initial laser optimization each night, so these data points give a good estimate of the high-order performance on the laser guide star. The laser return for all of the data points was fairly consistent at the equivalent of a V=12.4 star, although due to the size of the laser spot (average FWHM of ~2.8”), a significant amount of light is lost at the field stop (2.4” square), giving an apparent magnitude at the HOWFS of V=13.1. The noise in the data is most likely due to the variable seeing over these measurements (0.5-1.2 arcseconds in the visible).

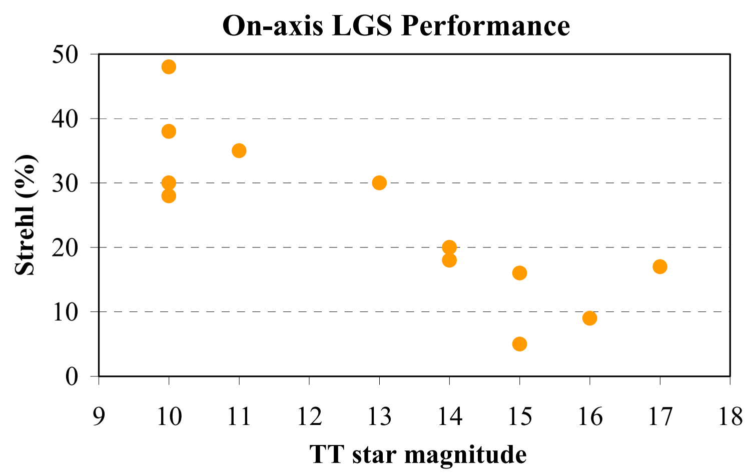

Figure 7 Measured K-band Strehl as a function of tip/tilt guidestar visible magnitude

4. BEAM TRANSFER AND LAUNCH SUBSYSTEM

The beam transfer system uses free-space optics to transport the 7W CSFL beam from the laser bench in the Coude lab to the focus of the laser launch telescope (LLT) located behind the Hale telescope secondary mirror (Figure 8). The first several components, located in the Coude lab, expand the beam to ~10 mm diameter, split off 0.5% to a beam diagnostics system (power meter, near- and far-field cameras), and direct the beam up the Hale telescope polar axis. A half-wave plate maintains the axis of linear polarization parallel to the telescope declination axis to maximize the transmission of downstream optics. The beam is next intercepted by a mirror mounted on a long-travel trolley on the south side of the telescope truss and directed up the south side of the telescope and across the top of a secondary spider vane to the LLT assembly. The LLT assembly is a beam expander consisting of a singlet lens and a Mangin design 45 cm diameter catadioptric telescope. The assembly also contains a second beam diagnostics bench and the UTT mirror. A quarter-wave plate located on the telescope optical axis converts the linearly polarized beam to circular polarization to maximize LGS return[4].

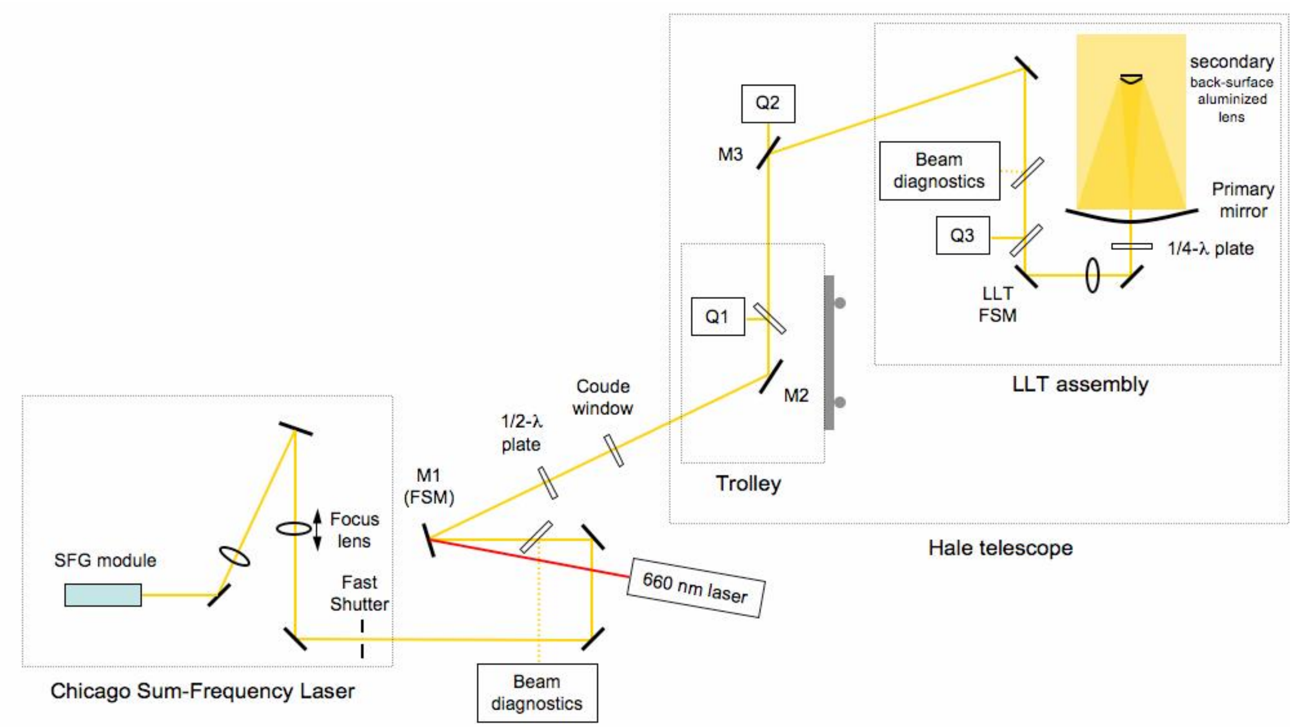

Figure 8 Schematic of the Palomar beam transfer system. Quad cell sensors Q1, Q2, and Q3 control servo mirrors M1, M2, and M3 to keep the laser beam centered on the laser launch telescope input pupil.

The beam transfer systems must compensate for significant flexure in the Hale telescope truss to maintain the laser beam alignment at the launch telescope entrance pupil. This is done using the output of three quad-cell detectors (Q1, Q2, and Q3 in Figure 8) to drive three actuated mirrors (M1, M2 and M3) in a servo system. Furthermore, the location of the trolley supporting M2 and the angle of the half-wave plate are commanded in open-loop as a function of telescope declination and hour angle, respectively. A software control system with a graphical user interface allows the AO operator to monitor the beam transfer system's status and insert a 660 nm wavelength stimulus laser for alignment and testing as necessary. However, during routine operation, the servo system acquires and locks on the laser autonomously.

A total of 28 air-glass or mirror surfaces are required to transport and format the laser beam from the CSFL bench output to the sky. We have measured the total transmission of the system at 589.2 nm to be 66.4%. Including typical atmospheric transmission of 86% at zenith, the total transmission from laser bench to mesosphere is ~57%.

The launch telescope wavefront quality has to date been a significant performance limitation of the system, with LGS spots typically 2.4" to 3" FWHM. We have recently identified the cause to be a flawed LLT secondary, and will be installing a replacement optic in June 2008.

5. SAFETY SYSTEMS

The Chicago laser is powerful enough to be hazardous to personnel on the ground, and a potential visual startle hazard to pilots flying aircraft through the beam. In order to safely propagate the laser to the sodium layer, we have implemented an interlock system at the 200” dome and an aircraft detection system consisting of a team of five human spotters, supplemented by three electronic sensors: a visible all-sky CCD camera, a boresighted infrared camera, and a boresighted radar.

5.1 Laser Safety Shutter

A normally-closed, high-speed laser safety shutter (Electro-Optical Products Corp. model SH-20-24) provides a fail-safe means to block the beam before it exits the laser optical bench without disrupting the operation of the laser. The actuation time of closure is 15 milliseconds. All the safety systems must provide open signals in order to open the shutter and keep it open.

5.2 Interlock Systems

All access points to regions of the dome and Coude room classified as laser hazard areas are protected by hardware interlocks that immediately shutter the laser when interrupted. These are wired to an alarm system whose output is hardwired to the shutter control relay.

A high-speed photodiode at the entrance of the laser launch telescope assures that the laser is aligned to the launch telescope at all times. If a positive signal is not received from this photodiode within 10 milliseconds of opening the laser shutter, then the laser will be immediately shuttered. During laser projection, if the same photodiode does not detect light for any period longer than 10 milliseconds, the laser will also be shuttered. Finally, the BTO computer provides a heartbeat signal to the shutter relay, which must be active for the laser shutter to remain open.

The telescope control system computer will provide a closed signal to the laser shutter relay if the Hale telescope (and attached laser launch telescope) pointing direction is not consistent with elevation limits, if the Hale telescope is slewing or if the dome shutter or windscreen are occulting the beam. The minimum elevation limit approved by the FAA is 45 degrees above the horizon.

5.3 Visible All Sky Camera

The All Sky Camera (ASCAM) system is a visible system designed to identify all aircraft that a human spotter might identify. The primary source of signal is the anti-collision strobe and wingtip navigation lights that the FAA requires for nighttime operations. The system is designed to detect aircraft up to an altitude of 120km and to shutter the laser before the aircraft crosses the beam. The response time of the ASCAM system is less than 9 seconds.

The ASCAM is a Santa Barbara Instruments Group STL 1001.E, with a Nikon F/2.8 fisheye lens, providing a 2π steradian field of view on a 1k x 1k pixel detector. The camera is mounted on top of the Hale telescope dome at Palomar Observatory. Its output is read continuously, providing a 3 second exposure every 7.4 seconds.

The images from the ASCAM are read into a dedicated computer running Red Hat Linux. This computer runs custom software which identifies the existence of an aircraft by subtracting the most recent exposure from a median of several previous frames (see Figure 9). If there is an aircraft moving through the field of view, it will appear as a light and a dark streak in the difference image. Any contiguous group of bright pixels in the difference image above a preset threshold will be considered a detection. The program is provided with the pointing coordinates of the laser projection telescope, and from the two data sets, predicts whether the detected aircraft is or is not within a 30degree-radius exclusion zone around the laser beam. From the midpoint of an ASCAM exposure to the decision point at which a "shutter close" signal is sent is approximately 5.7 seconds. The ASCAM system provides a signal to shutter the laser whenever a plane is detected in the exclusion zone.

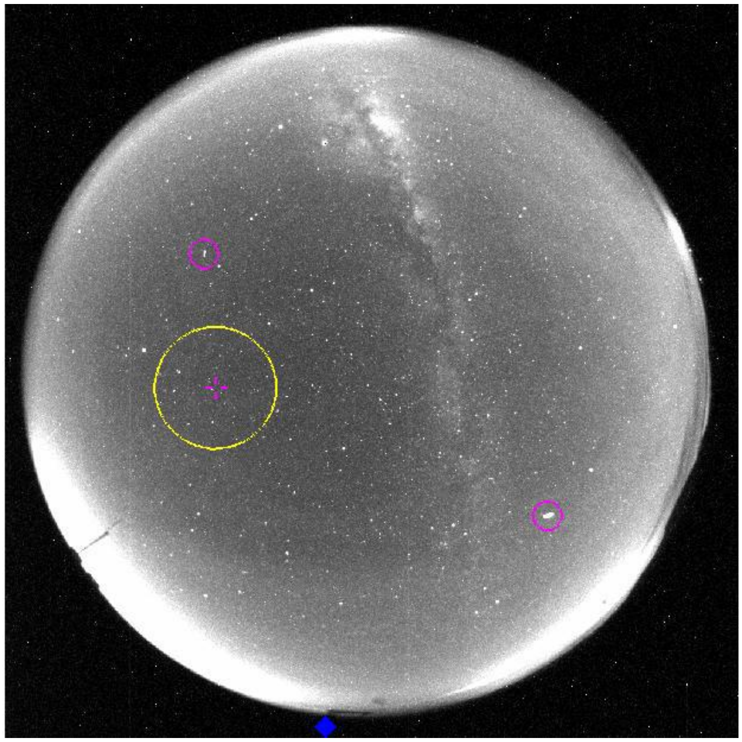

Figure 9 All sky camera image, with 2 aircraft highlighted by the automated detection software. The location of the laser projection point is marked with a pink cross. The exclusion zone is marked with a yellow circle.

5.4 Infrared Camera (IRCAM)

The IRCAM is a thermal-IR array that sees targets as a bright sources against the cold sky, regardless of illumination conditions, so it has the ability to detect unilluminated aircraft. The IRCAM also has the ability to observe an aircraft through moderate levels of clouds, dust and haze. Because it can be read out faster than a CCD array, the IRCAM provides more rapid response for the detection of low altitude or fast moving aircraft.

The IRCAM is an uncooled Indigo Merlin InSb MWIR camera with a 320 x 256 pixel microbolometer array detector. It is mounted inside the prime focus cage of the Hale telescope alongside the laser launch telescope. A warm shutter and internal calibration software allow self-calibration of the camera, performed at the start of each night. The camera has a 15x20 degree field of view and is boresighted with the laser launch telescope so it sees a cone of sky of at least +/- 7.5 degrees around the laser beam. The camera detector is read out continuously at 60 Hz frame rate.

The video stream from the IRCAM is fed into a frame grabber and analyzed for aircraft activity. The analysis software is identical to that used for the ASCAM. Any detection in the frame sends a signal to shutter the laser. The frame grabber runs at 4 frames/sec. From the midpoint of an IRCAM exposure to the decision point at which a "shutter close" signal is sent is 0.34 seconds. This system effectively protects aircraft more than 1000 ft above ground level.

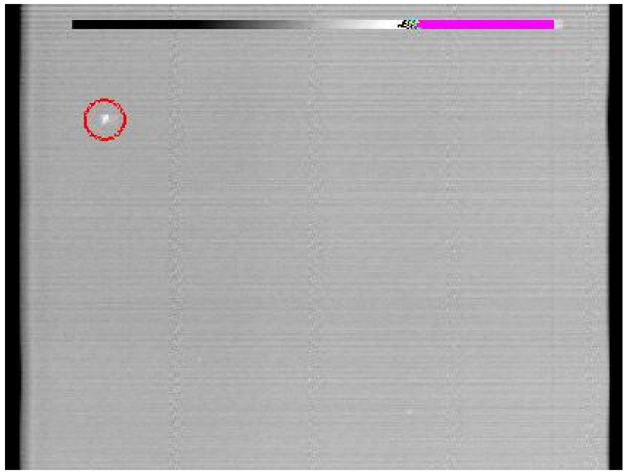

Figure 10 Infrared Camera image, with an aircraft highlighted by the automated detection software.

5.5 Boresight Radar

The final tier of the automated airspace safety system consists of a modified Honeywell Primus 400 weather radar, mounted on the top ring of the Hale telescope and aligned with the laser. Any aircraft which enters the radar conical field of view of 7.9 degrees in diameter will trigger the closure of the laser shutter with a latency of less than 45 ms, including radar transmission, detection, interlock relay actuation, and the closure time of the laser safety shutter. This is sufficient to protect aircraft traveling at 200 knots down to an altitude of 250 feet above the dome from inadvertent illumination. The boresight radar thus provides protection to all low-flying aircraft to which the longer latency IRCAM and ASCAM are insensitive.

5.6 Control Room Key Switch and Human Spotters

The final inputs to the laser safety shutter relay are the control room switches, consisting of a key switch to open the laser shutter, and two emergency shutoff switches which result in the immediate shuttering of the laser. Before and during laser propagation, two spotters outside the dome warn of aircraft which might approach a 30 degree zone of avoidance around the beam and call for the laser to be shuttered if an aircraft enters the zone of avoidance.

6. CONCLUSIONS

We have developed a sodium LGS AO system that can acquire stars in ~15 min and regularly achieve Strehl ratios of 30-35% on bright guide stars. This performance is limited by the laser return and spot size. We are working to correct the spot size problem which is due, at least in part, to an incorrect optic in the LLT. The system is currently being used for science at the Hale telescope at Palomar observatory.

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