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A NEW SODIUM GUIDESTAR ADAPTIVE OPTICS SYSTEM FOR THE STARFIRE OPTICAL RANGE 3.5 m TELESCOPE: POST PRINT

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14. ABSTRACT

A new adaptive optics is being installed on the Starfire 3.5 m telescope. Its uses the existing 50 watt pump to create a sodium guidestar. Transmission to the wavefront sensor is improved from 0.16 to 0.75.

15. SUBJECT TERMS

Active; Adaptive Optics; Atmospheric Correction; Astronomical Optics

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Abstract: A new adaptive optics system is being installed on the Starfire 3.5 m telescope. It uses the existing 50 watt pump to create a sodium guidestar. Transmission to the wavefront sensor is improved from 0.16 to 0.75.

OCIS codes: (010.1080) Active or adaptive optics; (010.1285) Atmospheric correction; (350.1260) Astronomical optics

1. Introduction

The Starfire 3.5 m telescope was designed for research in atmospheric compensation using adaptive optics for visible and near-infrared wavelengths. Its primary function is imaging low-Earth orbiting artificial satellites, although it has many potential applications in astronomical research. The telescope saw first light in 1994 [1], and a 30×30 subaperture natural guidestar adaptive optics system was commissioned in 4 years later in 1998 [2, 3]. A 50 watt sodium wavelength laser was installed in 2004 [4], and a prototype 15×15 subaperture sodium guidestar adaptive optics system produced science results in 2006 [5]. Also in 2006, the telescope gimbals and secondary mirror controls were completely upgraded with in-house designs using low-cost commercial components [6].

For the work described here, we have completely redesigned and optimized the adaptive optics system to take advantage of our sodium wavelength laser. The overall goal is to improve imaging for small, dim objects. We plan to produce near diffraction-limited images of dim objects at both I-band (850 nm) and J-band (1250 nm) wavelengths, and to demonstrate the ability to detect very dim non-resolved objects near brighter objects. Table 1 lists a comparison of key parameters for the adaptive optics systems. Figure 1 shows a schematic diagram of the new optical system.

Table 1. A comparison of key parameters for the adaptive optics systems on the Starfire 3.5 m telescope.

Parameter	Natural guidestar	Laser guidestar I	Laser guidestar II
first light	1988	2006	2010
subapertures	30×30	15×15	24×24
active subapertures	684	168	448
actuators	941	941	577
controlled actuators	756	189	480
tilt sensor format	2×2 pixel	2×2 pixel	4×4 pixel (tilt+focus)
wavefront sensor frame rate	500–1500 fps	500 fps	2000–4000 fps
wavefront sensor read noise	9 e–	6.5 e–	4–6 e– (0 e– APD array)
limiting magnitude	7	7	10–12
typical Strehl ratio	0.3	0.1	0.33

2. Optics

Since the prototype laser guidestar system was not optimized for sodium guidestars, transmission from the primary mirror to the wavefront sensor was only 0.16 at 589 nm wavelength. In the new system, significant design changes were made to optimize sodium guidestar transmission. We expect throughput for incoming 589 nm photons to be 0.75.

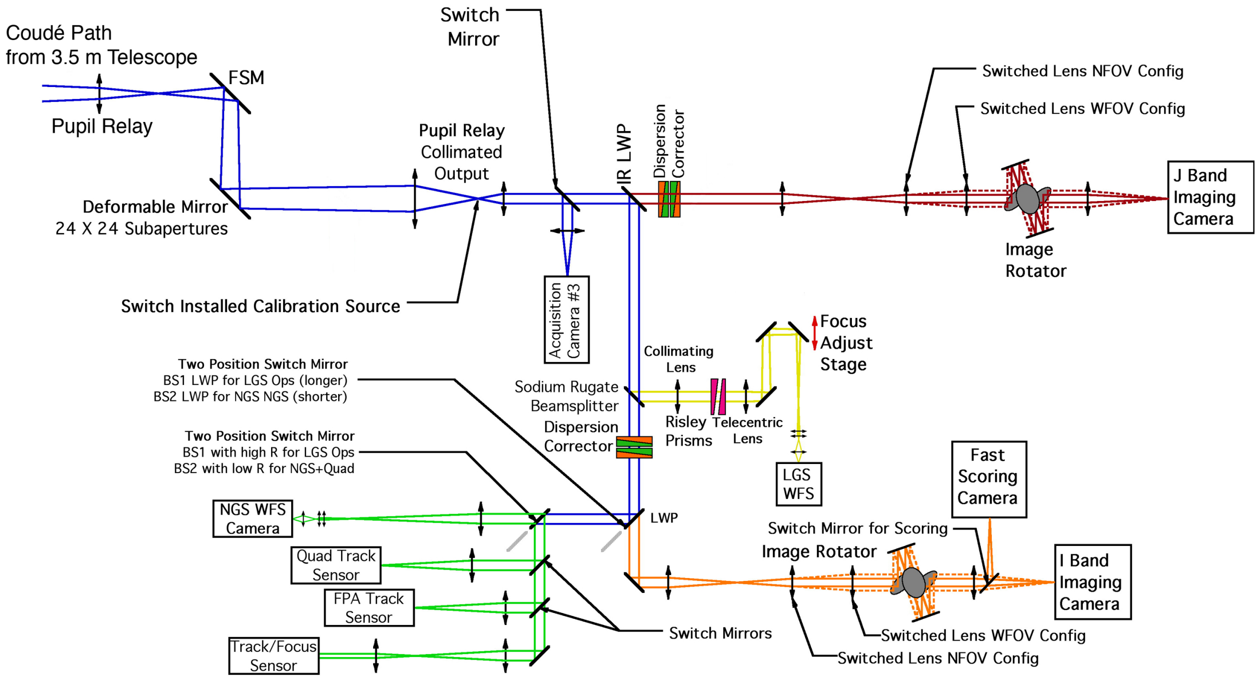

Fig. 1. Schematic diagram of the new optical system. The I-band bandwidth is 650–1000 nm, the J-band bandwidth is 1100–1350 nm, the tracker and natural guidestar wavefront sensor bandwidth is 480–640 nm, and the sodium wavefront sensor receives a narrow band around 589 nm.

We will improve the transmission by completely replacing every element in the optical path, except for the telescope primary mirror. The primary mirror, which has never been recoated, will receive a fresh coat of bare aluminum in our new chamber. The primary mirror figure and temperature controller will remain unchanged, as will the laser launch telescope and beam director. The secondary and coudé mirrors will be replaced with substrates with high-reflectivity broadband coatings. The tertiary mirror supports will be improved to reduce a nagging 23 Hz resonance.

The total number of surfaces downstream of the coudé path will be reduced. A K-mirror, which was used to derotate the entire optical path in the laboratory, has been removed in favor of individual image rotators for each of the science cameras; this eliminates three reflective surfaces. Instead of two fast tilt mirrors, one for coarse and one for fine tilt correction, a single fast tilt mirror with a large range of motion, has been procured. Lastly, the pupil relay between the tilt mirror and the deformable mirror has been eliminated. Instead, the telescope pupil is relayed to the deformable mirror while the tilt mirror is slightly displaced from a pupil. The Xinetics deformable mirror has an actuator pitch of 7 mm and an actuator range of 6.5 μm.

A second pupil relay after the deformable mirror generates a 40 mm collimated exit pupil. This is much smaller than the original design and reduces the size, footprint and cost of the downstream optics. The prescription of the telescope secondary mirror will change to increase the back focal distance. This reduces the unvignetted field from 1 mrad (200 arc-seconds) to 0.5 mrad (100 arc-seconds). Other important optical components include atmospheric dispersion correctors for wide bandwidth paths, Risley prisms for offset pointing, and image rotators for the science cameras. These rotating optical components will be controlled using electronics and software similar to the telescope gimbals and secondary mirror controllers.

3. Optical sensors

The new adaptive optics system requires sensors for high-order wavefront sensing, tilt and focus measurement, fast scoring, target acquisition, and imaging. The natural and sodium guidestar wavefront sensors will be MIT Lincoln CCID-66 charge-coupled devices (CCD). The CCID-66 is a 160×160 pixel frame-transfer CCD with 20 output ports each with 2-stage planar-JFET amplifiers. Read noise is expected to be 4 to 6 electrons at a 5 MHz pixel rate, yielding a read-out latency of about 100 μsec. These devices will later be replaced by MIT Lincoln Geiger mode avalanche photo-diode arrays (APD) [7], currently under development. Two sizes of APD arrays will be produced, 16×16 and

32×32 arrays of quad-cells detectors. These detector arrays are bonded to a CMOS read-out circuits with 10-bit counters. Read-out time is 20 μsec with no read noise. Development efforts are focused on reducing the dark count rate and pixel-to-pixel crosstalk.

When using the sodium guidestar, tilt and focus will be sensed using a small 2×2 subaperture Shack-Hartmann wavefront sensor with an APD array. These focus measurements will be used to drive a focus adjustment stage in the sodium wavefront sensor path. When using natural guide stars, tilt will be measured using either an APD quad-cell or discrete APDs with an optical pyramid. The fast scoring camera and focal plane array tracker will use CCID-66 sensors. The acquisition camera is a commercial camera with an e2v CCD-97, which is a 512×512 pixel frame-transfer electron multiplying CCD. The J-band science camera is a 1000×1000 pixel Teledyne HAWAII-1RG with InGaAs photo-diodes. The I-band science camera is under development; the interim sensor is an e2v 1004×1002 pixel electron multiplying CCD.

4. Electronics

The current adaptive optics processing electronics will be replaced with a custom packet switching network, greatly reducing the size and footprint of the electronics suite, while reducing processing latency. Functions of the network components include processing camera pixels, computing centroids, implementing least-squares phase reconstructors, and driving the deformable mirror, focus trombone for the wavefront sensor, and the fast tilt mirror. Data can be tapped and recorded at any point in the adaptive optics processing chain. In addition, we will include an auxiliary processor to allow analysts to test advanced algorithms using the C programming language, albeit at a lower closed-loop bandwidth.

5. Trade studies

Several trade studies were performed; two are summarized here. The first was deciding whether to put the adaptive optics on the telescope gimbals or in the coudé path. Four on-gimbal configurations were considered, (i) tip-tilt secondary with deformable tertiary, (ii) deformable secondary with tip-tilt tertiary, (iii) tip-tilt tertiary with deformable M4, and (iv) all optics at Cassegrain focus. Option (iv) was quickly eliminated because it would require significant modifications to the telescope mount. The other options were carefully studied with wave-optics simulations and throughput analyses. The environmental stability of the coudé path was chosen over the small advantage in throughput of the on-gimbal options.

We also studied the optimum number of subapertures. Two cases were studied using wave-optics and scaling-law codes, 24×24 and 30×30 subapertures. Turbulence strength, signal from the sodium beacon, and wavefront sensor read noise were varied while evaluating Strehl ratios. Except for the case where the signal from the sodium beacon was high (4000 photons/cm^2/s) and read noise was low (2 e–), Strehl ratios were higher for 24×24 subapertures. When the signal-to-noise ratio on the wavefront sensor is high, fitting error can be reduced by using more subapertures. However, when the signal from the sodium beacon was lower (2000 photons/cm^2/s), performance is improved by trading some fitting error for a higher signal-to-noise ratio on the wavefront sensor. Thus, we chose to use 24×24 subapertures for more consistent performance in less than ideal conditions.

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