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Matthew Britton, Viswa Velur, Nick Law, Philip Choi, Bryan E. Penprase, "CAMERA: a compact, automated, laser adaptive optics system for small aperture telescopes," Proc. SPIE 7015, Adaptive Optics Systems, 701516 (7 July 2008); doi: 10.1117/12.789973

Event: SPIE Astronomical Telescopes + Instrumentation, 2008, Marseille, France

CAMERA: A Compact, Automated, Laser Adaptive Optics System for Small Aperture Telescopes

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ABSTRACT

CAMERA is an autonomous laser guide star adaptive optics system designed for small aperture telescopes. This system is intended to be mounted permanently on such a telescope to provide large amounts of flexibly scheduled observing time, delivering high angular resolution imagery in the visible and near infrared. The design employs a Shack Hartmann wavefront sensor, a 12x12 actuator MEMS device for high order wavefront compensation, and a solid state 355nm ND:YAG laser to generate a guide star. Commercial CCD and InGaAs detectors provide coverage in the visible and near infrared. CAMERA operates by selecting targets from a queue populated by users and executing these observations autonomously. This robotic system is targeted towards applications that are difficult to address using classical observing strategies: surveys of very large target lists, recurrently scheduled observations, and rapid response followup of transient objects. This system has been designed and costed, and a lab testbed has been developed to evaluate key components and validate autonomous operations.

Keywords: adaptive optics, robotic telescopes

1. INTRODUCTION

In recent years, the astronomical community has witnessed laser guide star (LGS) adaptive optics (AO) systems commissioned on many of the 8-10 meter class telescopes.[1–4] These systems deliver diffraction limited image quality in the near infrared, providing a powerful new observational capability. With hundreds of science publications to date, adaptive optics is now having a significant impact on the field of astronomy. Still, the development model for facility class LGS AO systems, each costing well in excess of $10 million dollars and requiring significant operating expenses, is not transferable to smaller aperture telescopes.

Despite their comparatively small aperture, telescopes with apertures less than 5m present several advantages when equipped with an adaptive optics system. Smaller telescopes naturally permit an increased actuator density, which yields compensated images at visible wavelengths. Telescopes in this aperture class have been automated to provide survey and rapid response capabilities for seeing limited applications.[5–8] An AO-equipped robotic telescope would consititute a natural technical progression, while providing a novel observational capability. Finally, many small aperture telescopes are currently underutilized and in search of a new scientific mission. Telescopes provisioned with an AO system could be dedicated entirely to adaptive optics observations, substantially increasing the total amount of AO observing time. This would serve to disseminate the benefits of adaptive optics to a broader scientific audience.

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Adaptive Optics Systems, edited by Norbert Hubin, Claire E. Max, Peter L. Wizinowich,
Proc. of SPIE Vol. 7015, 701516, (2008)
0277-786X/08/$18 · doi: 10.1117/12.789973

The issues of automation and affordability present the greatest challenges to the realization of a robotic AO system. In the past decade, AO component technologies and computers have become significantly more reliable and less expensive. High power UV industrial lasers suitable for generating Rayleigh laser beacons, compact MEMS adaptive mirrors, and low-noise visible and infrared detectors are now commercially available. Computation and storage capabilities available through modern multiprocessor servers are more than adequate to drive an adaptive optics system for a small aperture telescope. Finally, the simplifications that arise from the use of a single computer afford the opportunity to fully automate the operation of an adaptive optics system. These component developments permit a significant reduction in the complexity and cost of an AO system.

In this paper we present a concept for a compact, autonomous MEMS-based Rayleigh AO system (CAMERA). The system provides compensated imaging at visible and near infrared wavelengths using commercially available components. CAMERA is designed to operate autonomously by selecting targets on the fly from a queue. This queue will be populated by users submitting observing targets over a web browser. This flexible, automated scheduling model minimizes observational overheads while permitting a rapid response capability. Section 2 discusses the scientific capabilities of such a system while Section 3 presents a reference design for CAMERA. Section 4 summarizes the performance estimates for this system. Finally, Section 5 describes a lab testbed constructed to evaluate the design and experimental queue scheduling software to control the system.

2. SCIENTIFIC CAPABILTIES

There are three broad categories of applications for which CAMERA provides novel observational capabilities. These applications take advantage of both the relatively large amount of time available on a small telescopes and the efficient operation enabled by a robotic, queue scheduled system.

- 1. Large surveys. High angular resolution surveys of thousands of targets would be extremely time-intensive on currently available AO systems. On a small telescope with a robotic AO system designed for low time overheads and queued, robotic operation, such surveys may be executed.
- 2. Monitoring. Robotic queued operation enables recurrent, regularly spaced observations of specific targets. Example programs include monitoring of planetary weather, binary orbit mapping, and followup of eclipsing binaries. This will permit programs that are difficult to pursue with existing AO systems on classically scheduled telescopes.
- 3. Rapid transient characterization. By responding autonomously to transient event alerts published over the internet, CAMERA can provide high angular resolution images of transient events a few minutes after notification is received.

These categories address a wide range of solar system, galactic and extragalactic astronomy. To illustrate the types of science enabled by CAMERA, two specific applications are described below in more detail.

2.1. Stellar and substellar companions to all types of stars

An AO-equipped small aperture telescope could perform the largest-ever survey for close companions to nearby stars. 10,000 stars could be observed to search for companions down to $\leq$1AU. The survey would allow the first detailed characterization of the companion population in an single unbaised sample spanning essentially the entire nearby stellar mass range. Two minute exposure times in I & H-bands are sufficient to detect and start to characterize high-mass brown-dwarf companions at separations of $\geq$1.0 arcsec from the target stars. The sensitivity to closer companions will depend on the brightness of the target stars; brown dwarfs are readily detectable down to at least 5 AU separations around M-dwarfs. This survey would require about 4 months of telescope time. Candidate companions would be incorporated into the observing queue for common proper motion companionship confirmation and to establish the initial astrometric measurements vital to pin down the mass-to-luminosity relation. The very large sample size enables excellent statistical constraints on the variation in binary properties as a function of mass, as well as a sensitive search for the most interesting exotic multiple systems such as close white-dwarf / brown-dwarf pairs.

2.2. Transient Characterization

Optical transient astronomy is currently a growth area. New and future transient projects such as PanSTARRS,[9] the Palomar Transient Factory and LSST[10] are expected to generate hundreds of thousands of new optical transients, from which the most interesting must be selected for followup with large aperture, AO equipped telescopes. There is a clear need for facilities capable of rapidly characterizing interesting faint transients without using costly large-telescope observing time.

CAMERA's ability to deliver greatly improved SNR in the near-infrared is particularly important for quick and efficient transient characterization. Beacuse of the high sky background in the NIR, programs that require photometry at these wavelengths can be executed one to two orders of magnitude more quickly using a high-angular-resolution imaging system compared to a seeing-limited system on the same telescope. This improvement can make a substantial difference to the followup capabilites for higher-redshift objects. For example, possible gamma ray bursts subject to the Gunn-Peterson trough will require NIR characterizations, and even moderate redshift supernovae are only detectable by current surveys in their peak emission in I and z bands.

CAMERA is able to obtain 10% photometry on 23-magnitude objects in the V, R, I, z, J, H filters in only thirty minutes total. A similar characterization program using a seeing-limited system would require approximately one night per transient on a 1.5m seeing-limited telescope, chiefly limited by the observing time required in the red. CAMERA would offer a far cheaper approach to light-curve measurement of large samples of high-redshift transients than seeing-limited instrumentantion on a large network of small telescopes – or AO observations on large telescopes.

High angular resolution is also useful for transients that occur in crowded fields or nebulous environments. In this way, CAMERA can make the difference between confirming a transient and immediately disentangling its environment. (Is there nearby nebulosity? Is it hosted in a faint galaxy? Is it really associated with a precursor noted in HST images?) As the number of detected transients increases, the demand for such measurements is likely to grow.

An important limiting factor for AO observation of transients, which can occur anywhere on the sky, is the probability of having a suitable reference star nearby to the transient. Although not all transients can be covered, in Section 4 we show that the system described here offers sky coverage fractions of order 20%. Given the expected high rates of transient detections in planned survey programs, CAMERA will not be target-limited.

3. THE CAMERA DESIGN

This section summarizes the design choices made for CAMERA. Each of the major components are discussed below. The software architecture and operational model are also described. Figure 1 shows

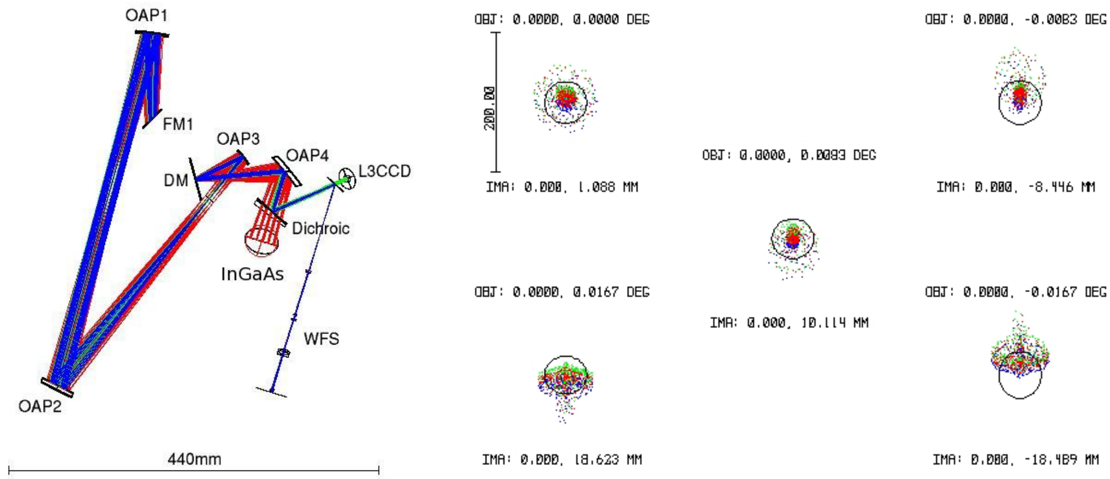

Figure 1. The CAMERA backend optical design. The left panel shows a raytrace of the optical system. An F/8.75 beam from the secondary mirror enters the system from FM1, which serves as the tip tilt mirror. A first stage of magnification is provided by the first pair of off axis parabolas (OAP's). The off axis parabola OAP3 collimates the beam and reimages the telescope pupil plane onto the MEMS deformable mirror (DM). The output of the final OAP4 is split by a dichroic. Red light is directed to the InGaAs detector, while the remaining light is directed onto the electron multiplying CCD (L3CCD). A second dichroic is used to split the 355 nm laser light into the wavefront sensor (WFS). As indicated, the relay is about a half meter on a side. The right panel shows spot plots for this optical design over a 2 amin field. The black circle corresponds to the the first Airy minimum at 600 nm, indicating good image quality delivered by this system. This design has been aligned and proven in the laboratory.

the optical relay design for the AO backend and the image quality in the focal plane. Figure 2 shows key components of the system and solid body images of the design.

Adaptive Mirrors

CAMERA utilizes commercial adaptive mirrors for high order and tip tilt wavefront control. High order compensation is performed by a 12x12 actuator MEMS device from Boston Micromachines Corporation. This device was chosen for its low cost and its small, 4.4 mm active surface. For a 1.5 m telescope the actuator density is adequate for providing compensation at visible wavelengths, while the 3 μm mirror stroke is more than sufficient to perform atmospheric wavefront compensation. The small active surface of the MEMS device permits a compact optical design, in which all optics are 2 inches or less in diameter. Tip tilt compensation is performed using an S330 piezo tip tilt stage from Physik Instrumente.

Laser Beacon

CAMERA will employ a 355 nm laser broadcasted to 10 km as a laser beacon. This altitude constitutes a compromise between laser return and the effects of focal anisoplanatism. The UnISIS laser guide star system at Mt. Wilson employed a 351 nm laser, and received FAA clearance to broadcast at this wavelength without aircraft safety measures such as human spotters or radar systems.[11] This is a strong incentive to employ an ultraviolet laser. The return flux will be range gated over 650 m to mitigate the effects of spot elongation in the wavefront sensor. The estimated photoreturn provides adequate signal

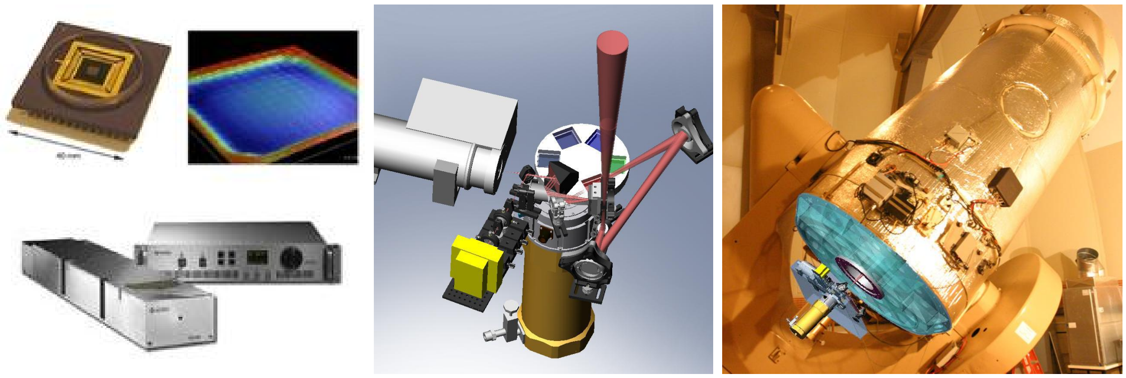

Figure 2. Elements of the CAMERA system. On the left is shown a MEMS device from Boston Micromachines Corporation used for high order wavefront control and a 355 nm Q-switched solid state laser used to generate the Rayleigh beacon. The center panel shows a solid model of the CAMERA backend relay, including the wavefront sensor and two science detectors. The small MEMS device permits a compact optical design that occupies much less than a cubic meter of space. The right panel shows this solid model mounted to the back of the 1.5m telescope at Palomar Observatory.

to noise ratio to drive the adaptive optics control loop. The CAMERA design incorporates a JDSU Q301-HD all solid-state Q-switched diode pumped tripled ND:YAG laser. The nominal power output of this laser is 10 Watts at 10 kHz repetition rate. This laser uses Lightwave Electronics Corp. original Direct Coupled Pump gain modules, which are known for their efficient and rugged design. Suitable glasses will be chosen for use in the backend optical relay to avoid fluorescence from 355 nm light.

Detectors

The CAMERA design incorporates two science-grade detectors to offer dual band imaging capability at near infrared and visible wavelengths. A 320 x 256 InGaAs detector will be employed as an infrared sensor. This 0.9 - 1.7 μm detector offers 3 e- noise, 1 e-/sec dark current, and a fast region of interest sampling mode.[12] An electron multiplying 1k x 1k EMCCD from Andor Technology will be used for visible imaging and laser acquisition. This camera also offers a fast frame readout mode, which may be utilized for applications requiring short exposure times and frame selection. Light from the science field will be split by a dichroic to feed these two cameras, and the 355 nm laser light will be separated from the visible channel using a second dichroic.

Laser guide stars are incapable of sensing atmospheric tilt, and a natural guide star is required for tilt tracking. CAMERA performs tilt tracking in the science focal plane using one of the two science cameras, depending on the observational program. Both detectors offer the capability of reading out small regions of the detector at frame rates exceeding 100 Hz. These modes may be used for high frame rate readout of a small region containing the natural guide star. Tilt tracking is then performed on these images using standard centroid algorithms.

CAMERA uses a Shack Hartmann wavefront sensor, which is based on a SciMeasure camera containing an EEV CCD 39 chip from E2V. This camera has been proven to run at rates up to 2 kHz at 7e- read noise, and at 800 Hz with 3.7 e- read noise, and is used in the Palomar adaptive optics system on the Hale 5m.

Computational Architecture

A central concept in the CAMERA design is the ability to perform real time wavefront sensing and control and to coordinate the science detectors and peripheral hardware using a single commercially available server. This strategy minimizes latency, software fragmentation, and overall system fragility. A quad-core AMD Opteron server has been chosen for this purpose. Image frames are transferred from the cameras into memory via PCI card. For the wavefront sensor image data, centroiding and reconstruction are performed in real time on one of the processors, and updated commands are transferred via PCI cards to the MEMS device. The low actuator count of the MEMS device permits these operations to be performed at loop rates of order 1 kHz. Tilt sensing and control is performed in an analogous fashion. Multiple processors are used to isolate those computational activities which require low latency from other tasks. In addition, this server is used to drive the telescope and sequence the laser, and to provide control of other hardware elements in the system.

The use of a single server permits an integrated approach to remote system access and logging functionality. Control software for CAMERA utilizes C++ library code to configure and query hardware elements in the system. This multithreaded code achieves a high degree of abstraction and modularity through the use of templates and generic programming techniques. The code is integrated into a web application that exposes this functionality over a secure port accessable via web browser. In this way, hardware elements in CAMERA may be monitored remotely over the internet. Similarly, this executable offers a set of system tests that may be executed over a browser. Examples include common adaptive optics calibration tasks such as measurment of centroid gain curves. Input parameters for these system tests are specified via an HTML form interface and results stored in a web-browsable archive to maintain a historical record of system performance.

Operations

The CAMERA system will support two different types of automated observations. First, the system will perform automated execution of observations from a queue populated by astronomical users submitting targets via HTML form interface. In this mode of operation, observations are selected from the queue based on target observability and are executed robotically. Second, the server will monitor and respond to transient alerts from VOevent feeds.[13] In this way, CAMERA will be able to respond rapidly to transient alerts, while utilizing the remaining time to execute survey and monitoring observations. Startup and shutdown procedures will be executed each night to log status and performance of the hardware and to execute standard calibration routines. The software implementation of these automated observations is entirely analogous to the system tests described in the previous section. Observational data products will be stored in a web-browsable archive for retrieval by the astronomical user.

4. CAMERA SYSTEM PERFORMANCE

The system performance predictions for CAMERA are presented in this section. These performance predictions were evaluated assuming the median turbulence profile at Palomar Observatory, which has been computed from a year of DIMM/MASS data. The on-axis error budget is shown in Table 1. Simulated long exposure point spread functions (PSFs) that reflect this error budget are shown in Figure 3, and indicate that CAMERA will deliver FWHM image quality of .1" at .9 μm and .2" at 1.6 μm. The Strehl ratio vs. wavelength is also shown in this figure, illustrating that CAMERA delivers partial compensation well into the visible. The sensitivity of the CAMERA system was evaluated by coupling these PSFs into a single pixel of the science detectors and evaluating contributions from read

Term	**Error**	**Notes**
Focal Anisoplanatism	78 nm	Assumes 10 km beacon
Servo Error	53 nm	Assumes f_G= 37 Hz, f_s = 77 Hz
Fitting Error	60 nm	For a 12x12 actuator deformable mirror
Measurement Error	65 nm	Assumes 10 W, 355 nm laser, 7e- read noise
Uncorrectable telescope aberrations	40 nm	Based on Hale 5m polishing errors
Contingency	75 nm	
High order error budget	153 nm	
Residual Tilt Jitter for mH=13.7 TTGS	65 mas	TTGS coincident with LGS
	135 mas	TTGS 30" from LGS

Table 1. Guide star error budget for CAMERA. Measurement error accounts for transmission losses in the atmosphere and optics. Residual tilt jitter was computed assuming H band focal plane tilt sensing of an mH=13.7 guide star. This star is partially compensated by the AO system, and this compensation degrades with angular offset from the laser. These calculations assume median turbulence conditions at Palomar Observatory: seeing = 1.1 asec, r_0 = 9 cm , θ_0 = 2 asec , and d_0 = 1 meter for a 10 km beacon.

Band	**Sky Bgd. (mag/asec^2)**	**5min Magnitude Limit**	**5 min CAMERA SNR**	**5 min SL SNR**	**Integration Time Ratio**	**λ/D (mas)**
V	20.5	22.5	10	10	1.0	72
R	20	23.2	10	5.3	3.5	81
I	19	24.1	10	1.9	27.7	122
J	16.4	23.5	10	1.0	100.0	169
H	15	22.6	10	1.2	69.4	223

Table 2. CAMERA sensitivity and integration time advantages. The third column lists the point source magnitude that yields an SNR of 10 in five minutes of integration time with CAMERA. The fifth column lists the SNR delivered by a seeing limited system, while the sixth column lists the integration time required to reach this sensitivity. The final column lists the diffraction limited angular resolution on a 1.5 m telescope. The calculations assume an m_V=13 guide star for tilt tracking and median turbulence conditions at Palomar Observatory.

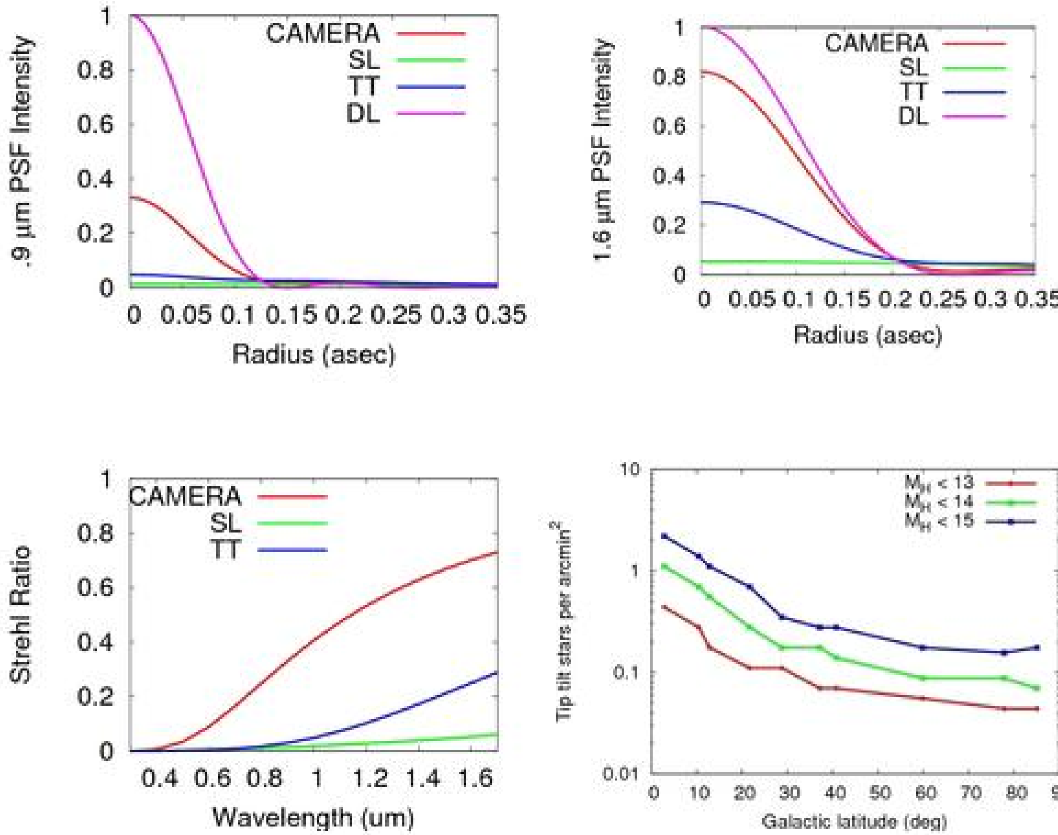

Figure 3. CAMERA point spread function, Strehl ratio, and sky coverage predictions. The upper panels show radial cuts through the on-axis 0.9 and 1.6 μm PSF's delivered by CAMERA. For comparison, cuts through the diffraction (DL), seeing limited (SL) and tip tilt compensated (TT) PSFs are shown. The lower left panel shows Strehl ratio vs. wavelength for the CAMERA system, and for seeing limited and tip tilt corrected observations. CAMERA offers significant benefits in angular resolution and sensitivity over TT and SL systems. The lower right panel shows stellar density vs. galactic latitude. CAMERA is capable of tip tilt guiding on an $m_H = 13.7$ star with residual jitter between 65 and 135 mas, depending on the offset of this star with respect to the laser beacon. At this level of performance, sky coverage is nearly complete in the galactic plane, and drops to about 10% at the poles. The H band stellar density as a function of galactic latitude was taken from the 2MASS Point Source Catalog reference fields.

noise, dark current and sky background. An analogous calculation was performed for a seeing limited system with 1.1 asec sampling. The results appear in Table 2, and indicate significant improvements in the sensitivity of CAMERA redwards of R band when compared to observations in the seeing limit on a 1.5 m telescope.

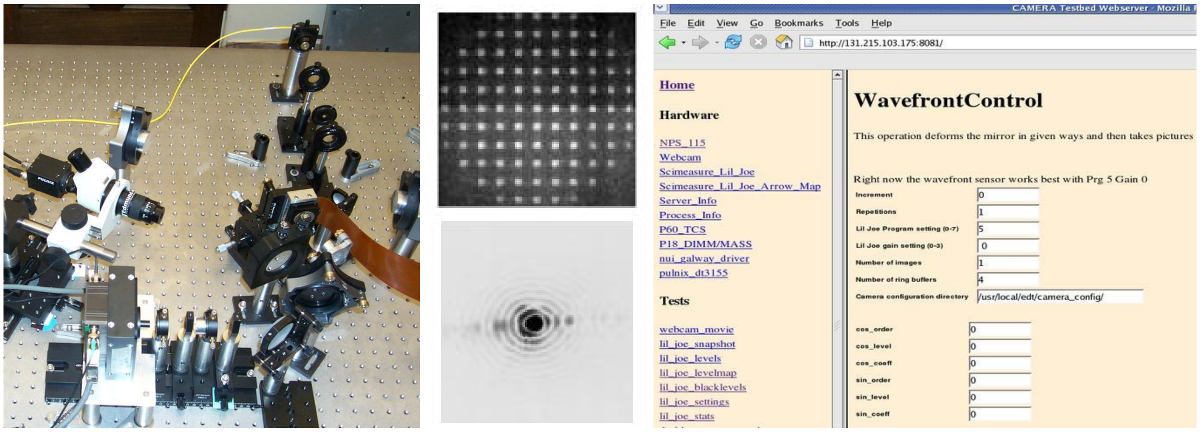

Figure 4. The CAMERA testbed in the lab at Caltech. The left panel shows the optical relay. The MEMS device is connected by a copper-colored ribbon cable to its electronics drivers, while the Shack Hartmann sensor lies along the lower edge of the panel. The center panels show the 11x11 array of lenslet spots incident on the wavefront sensor camera and the resulting point spread function imaged by the science camera. The right panel shows a screenshot of a web browser, from which the CAMERA hardware may be monitored and system tests executed from a remote location. Users enter the parameters of the test into an HTML form interface, and receive the results over the browser upon completion of the test.

5. CAMERA TESTBED

Design and development for the CAMERA project is at a mature state, and many of the major system concepts and components have already been demonstrated. Design work for the CAMERA optical and optomechanical systems is well underway, and all major hardware devices have been selected and costed. As part of this development effort, a testbed for CAMERA has been constructed at Caltech. This testbed is shown in Figure 5, and contains the optical relay, the Shack Hartmann wavefront sensor and the MEMS device that will be used in the final system. A multiprocessor server is employed for real time sensing and control, and to sequence hardware and archive the resulting data products. The testbed is controlled via a web browser, from which hardware status may be monitored in real time and tests may be executed via HTML form interface. At present, closed loop adaptive compensation of phase aberrations introduced by a rotating plate has been demonstrated initially at a control loop rate of 100 Hz. Further software optimization will enable the higher loop rates required for atmospheric sensing and control.

An experimental version of the queue scheduling software for CAMERA has also been developed. This software resides on the CAMERA control computer and acts as a webservice for astronomical users. This software design is based on the concept of having multiple observing programs, each of which is owned by a particular user. Each observing program has its own target list and observing results, which may be inspected and managed by the owner of the observing program via a web browser. Content is password protected to restrict access by unauthorized users.

Conceptually, observational targets pass through two distinct phases: ingestion and observation. In the ingestion phase, targets may be submitted by users via an HTML form interface, or may be retrieved from a VOevent feed. During this ingestion process, queries of the 2MASS,[14] SDSS,[15] and NOMAD[16] catalogs are performed to compile lists of nearby stars. At this time existence of a tip tilt guide star is ascertained for each target proir to placing the target onto the queue. Those targets that lack an appropriate tip tilt star are rejected. The resulting catalog information and finding charts are assembled into a user accessable web page.

During operations, software selection of targets from the queue is based on observability, slew time and telescope time allocation policies. Transient response observations are supported by monitoring VOevent feeds on the internet, and upon reception of such an event regular observing will be interrupted in favor of transient followup. Once a target has been selected, the CAMERA software drives the telescope to the target, broadcasts the laser, acquires the laser beacon onto the wavefront sensor using images from the CCD, and locks the AO control loops. Tilt tracking is performed using one of the two science cameras, which may be operated at high frame rate in a subarray mode. Filter settings, exposure times, and dither patterns specific to each observing program are coordinated through software. Upon completion of an observation, the target is dequeued and a web page is assembled with links to the observing results and related information. These pages are visible to the astronomical user through the webservice.

6. CONCLUSIONS

The CAMERA project speaks to a number of current issues in astronomy and astronomical adaptive optics. By providing large amounts of flexibly scheduled AO observing time, CAMERA enables cost-effective science that is complementary to AO-equipped 8-10m class telescopes. The project targets the emerging field of time-domain astronomy: a high-profile, mainstream astronomical application that is driven by a large investment in ground-based survey telescopes. The CAMERA system is designed for small aperture, robotic telescopes. Telescopes in this aperture class are currently underutilized and in search of new scientific missions.[17] Finally, the project targets an area that has historically been a weak point for adaptive optics: automated operations. For these reasons, successful deployment of this automated AO capability on the robotic 1.5m telescope would constitute a significant evolutionary step in the field of astronomical adaptive optics.

7. ACKNOWLEDGEMENTS

Many colleagues have contributed their support and advice to the CAMERA project. The authors gratefully acknowledge discussions with Andrew Pickles, Roger Smith, Richard Dekany, Laird Thompson, Mitch Troy, Chris Shelton, Michael Ireland, Shri Kulkarni, Judy Cohen, and Lynne Hillenbrand. The authors also thank the UCSC Lab for Adaptive Optics for characterizing the MEMS device used in the CAMERA testbed.

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