**Final Report for Period:** 07/2011 - 12/2011  
**Submitted on:** 03/29/2012  
**Principal Investigator:** Smith, William S.  
**Organization:** AURA  
**Submitted By:**  
Smith, William - Principal Investigator  
**Title:**  
Administration by NOAO of the Adaptive Optics Development Program (AODP)

### Project Participants

<table>
<thead>
<tr>
<th>Name</th>
<th>Worked for more than 160 Hours</th>
<th>Contribution to Project</th>
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</thead>
<tbody>
<tr>
<td>Smith, William</td>
<td>Yes</td>
<td>PI, AURA President</td>
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<tr>
<td>Mould, Jeremy</td>
<td>Yes</td>
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</tbody>
</table>

### Senior Personnel

- **Name:** Smith, William
- **Worked for more than 160 Hours:** Yes
- **Contribution to Project:** PI, AURA President

- **Name:** Mould, Jeremy
- **Worked for more than 160 Hours:** Yes
- **Contribution to Project:** NOAO Director

- **Name:** Silva, David
- **Worked for more than 160 Hours:** Yes
- **Contribution to Project:** NOAO Director

- **Name:** Strom, Steven
- **Worked for more than 160 Hours:** Yes
- **Contribution to Project:** Project Administration and Scientific Oversight

- **Name:** Ridgway, Stephen
- **Worked for more than 160 Hours:** Yes
- **Contribution to Project:** Project Administration and Scientific Oversight

- **Name:** Sprayberry, David
- **Worked for more than 160 Hours:** Yes
- **Contribution to Project:** Project Administration and Scientific Oversight

### Post-doc

### Graduate Student

### Undergraduate Student

### Technician, Programmer

### Other Participant

### Research Experience for Undergraduates
Organizational Partners

University of California-Berkeley
Provided facilities, collaborative research, and in-kind support for sub-award C33001T, 'A Noiseless Imaging Detector for Adaptive Optics with Kilohertz Frame Rates,' amount $900,233.

California Association for Research in Astronomy
Provided facilities, collaborative research, and in-kind support for sub-award C33002T, 'Development of the Next Generation of Optical Detectors for Wavefront Sensing,' amount $1,080,981.

Lawrence Livermore National Laboratory
Provided facilities, collaborative research, in-kind support for sub-award C33003T, 'Pulsed Fiber Laser for Guide Stars,' amount of $1,500,000 and sub-award C33004T, 'Development of Large Deformable Mirrors Based on Dense Actuation of Nano-Laminate Membranes,' amount $987,841.

Coherent Technology, Inc.
Provided facilities, collaborative research, in-kind support for sub-award C33005T, 'Compact Modular Scalable Versatile LGS Architecture for 8?100 m Telescopes,' amount $3,295,235.

G.A. Tyler Associates, Inc
Provided facilities, collaborative research, in-kind support for sub-award C33006T, 'Practical and Analytic Assessment of Adaptive Optics Concepts Required to Provide Atmospheric Compensation for the Next Generation of Large Ground-Based Telescopes,' amount $201,019.

Other Collaborators or Contacts

None

Activities and Findings

Research and Education Activities:
See Findings Section.

Findings:
   Goal: To develop and test at least one prototype for a very rapid-readout, low-noise, optical detector that could be useful for adaptive optics (AO) wavefront sensing (WFS) systems.
   Activities: The project resulted in the successful fabrication of an optical imaging tube consisting of a pair of micro-channel plates (MCPs) read out by a complementary metal-oxide-silicon (CMOS) application-specific integrated circuit (ASIC) developed for X-ray imaging called the Medipix2. The Medipix2 is an array of 256 x 256 pixels, each of which amplifies and counts individual photon-stimulated events amplified by the MCPs. A multi-alkali photocathode installed in proximity focus above the MCP is used for conversion of incoming photons into photoelectrons. The Medipix2 integrates these detected photons, and the binary values of these counters are read fast (approximately 1 kHz frame rate) and without readout noise.

   Goal: To develop and test at least one prototype each of two new types of charge-coupled device (CCD) optical detectors that could be useful for AO WFS systems. The first type would attempt to achieve lower readout noise without sacrificing?and, if possible, improving?readout speed using two different methods: (1) develop lower readout noise amplifiers using a planar junction field effect transistor (JFET) design from the collaborator at Massachusetts Institute of Technology/Lincoln Labs (MIT/LL), and (2) design the CCD with more readout ports. The second type of CCD would employ a custom layout to optimize the number and geometry of the pixels for use with laser guide star (LGS) systems.
Activities: For the first type of device, the team developed a 160 x 160-pixel, split-frame transfer CCD with 20 video outputs (10 on each frame/side), with each output employing 2-stage amplifiers with a planar JFET first stage. This device is optimized for use with natural guide star (NGS) systems on current large (8-meter to 10-meter) telescopes. The team also developed two experimental versions, one with a 256 x 256-pixel geometry and 64 video output channels, and one with a 1k x 1k-pixel geometry and 16 video outputs. This development proceeded incrementally through several wafer runs, finally resulting in functioning, full-featured versions of these CCDs. For the second type, the team designed a prototype of one quadrant of a polar-coordinate detector, with the pixel geometry being a function of radial distance from the center of the parent circle. This device had 724 active subapertures, each 30 x 30 pixels, and a total of 32 video outputs with each output having a 2-stage planar JFET output amplifier. This prototype device was fabricated only in the last wafer run.

Goal: Demonstration of the major subsystems for, and the combined system operation of, a prototype 589-nm, 10-Watt average power, pulsed laser system.

Activities: The project involved the development and demonstration of two input lasers, each providing 12 Watts of power into the final mixing stage that produces the 589-nm light. One input laser worked at 938 nm using neodymium-doped fibers and the other worked at 1583 nm using erbium-doped fibers. Both lasers operated in pulsed mode with a repetition rate of 500 kHz and a 10% duty cycle. The original optical fiber used in the gain coil of the 938-nm input laser was found to have out-of-specification losses induced by the fiber cladding, which resulted in overheating of the gain coil and catastrophic failure after modest dust accumulation. This fiber was replaced at no cost by the manufacturer with a fiber coil that did meet specification, allowing the 938-nm input laser to achieve 11.5 Watts of output power (the target was 12 Watts). The 1583-nm input laser performed satisfactorily, meeting its goal of 12 Watts of output power after the custom-built, fiber gain coil system was implemented; an earlier attempt to use commercial-off-the-shelf amplifiers designed for continuous-wave mode failed to provide the required stability at the necessary pulse rates and beam qualities. The input lasers were sum-frequency mixed in a periodically poled stoichiometric lithium tantalate crystal to generate the required output light of 589 nm.

4. Sub-Award C33004T, 'Development of Large Deformable Mirrors Based on Dense Actuation of Nano-Laminate Membranes,' Lawrence Livermore National Laboratory.
Goals: Development of dense actuation on nanolaminate (NL) mirrors by attaching them to closely spaced microelectromechanical (MEMS) actuators. This will require the development of (1) suitable MEMS actuators, (2) nanolaminate foils, and (3) a method for bonding the nanolaminate to the MEMS actuator matrix.

Activities: The work proceeded through two generations of devices. The first generation was a small NL foil attached to a single MEMS chip with approximately 100 conventional MEMS actuators. The second generation used a larger foil and a MEMS device with approximately 1000 custom-designed actuators. During the first stage, the project devoted considerable effort to the production of NL foils that were thin enough to work as deformable mirror surfaces, strong enough to survive the fabrication and bonding processes, and flat enough to make mirrors of suitable optical quality. Several stages of experimentation and analysis went into the vacuum deposition process used for original fabrication of the foil, the choice of substrate materials, and the techniques for removing the foils from the substrates after deposition. In the second stage, work focused on the design of the MEMS matrix to allow direct control of each element in the large matrix and to keep the forces applied by the elements within the range that can be tolerated by the NL foils?that is, robust enough to handle the stresses of bonding to the foil and still be within the abilities of the commercial fabrication subcontractors to build.

5. Sub-Award C33005T, 'Compact Modular Scalable Versatile LGS Architecture for 8?100-m Telescopes,' Coherent Technology, Inc. (later Lockheed Martin Coherent Technology).
Goals: Development of a new, highly versatile, solid-state architecture for a sodium-wavelength laser guide star (LGS) system. The two new and critical elements of the system are: (1) a versatile low-power master oscillator modulated by a telecom-heritage commercial-off-the-shelf fiber modulator to generate a temporal and spectral format tailored to the unique needs of sodium layer interaction presented by several different astronomical applications (multi-conjugate adaptive optics, Rayleigh scattering compensation, and spot-elongation compensation); and (2) compact amplifier chains that implement self-imaging waveguide technology to achieve the required high gain without significant noise or distortion of the beam or waveform.

Activities: The work proceeded in two phases. In Phase 1, the team demonstrated each of the subsystems separately: the 1064-nm laser preamplifier with versatile waveform generator, the 1319-nm laser preamplifier with versatile waveform generator, development of the crystal sum-frequency mixing system, and the 589-nm output laser at 20 Watts of output power (sufficient for current 8-meter and 10-meter telescopes). A number of early issues with low input power and reduced efficiency were addressed by separating the pulse formats (slow and fast) so that the 1064-nm input leg used the slow (250 microseconds) format and the 1319-nm input leg used the fast (3 microseconds) format. This required modification of the waveguides on each side, which in turn led to beam quality issues that the team addressed through active control of beam alignment and jitter. When mixing the input beams, the team identified low conversion efficiency due to non-uniform beam
quality along the length of the mixing crystal. In Phase 2, the team addressed these issues by improving the design and fabrication of the waveguides. The team also adopted longer mixing crystals to improve mixing efficiency, especially at higher input powers. Finally, the team restored the identical pulse formats between the two input legs, also to improve mixing efficiency, which required adoption of free-space, as opposed to fiber-coupled, power amplifier stages on both legs.


Goals: Assessment of the feasibility of implementing certain advanced atmospheric tomography and wavefront reconstruction algorithms in real-time processing hardware to achieve the performance goals required for adaptive optics systems planned for extremely large-aperture (20-30 meters) telescopes.

Activities: The team considered three distinct algorithms: Preconditioned Conjugate Gradient (MG-PCG), Fourier-Domain Preconditioned Conjugate Gradient (FD-PCG), and Order-N Tomography (ONT). They considered existing processing technology, such as the latest generations of digital signal processors (DSPs) and field-programmable gate arrays (FPGAs), and they created hybrid architectures optimally suited for each of the three algorithms. They also developed wave-optics simulations of the three algorithms for a 30-meter aperture, and, finally, they evaluated each algorithm's ability to correct for atmospheric turbulence over the 30 arcsecond field of view required for most diffraction-limited science cases at extremely large telescopes.

Findings

Findings: Testing of the complete prototype system revealed a quantum efficiency (QE) significantly lower than expected (peak value of 3.8% at 410 nm, a factor of almost 4 lower than prior experience). The poor QE was attributed to the 'by hand' fabrication process for the multi-alkali photocathode employed in the lab. Other important properties of the system, including response uniformity, spatial resolution and spatial linearity, and dynamic range above background, yielded satisfactory results relative to the requirements of an astronomical WFS.


Findings: Development of the low readout noise, rapid readout devices (the 'first type' referred to above) proceeded in three generations. In the first generation, the team found that use of a single-stage readout amplifier did not noticeably reduce the readout noise. Based on this finding, the second generation of devices employed a two-stage amplifier that allowed significantly faster readout rates without significant increases in readout noise. These devices achieved 500 kHz pixel rates (equivalent to readout in approximately 0.05 sec for this size of device) with an average read noise of approximately 1.3 electrons. These devices were found to exhibit variations in responsivity from output to output over the 20 outputs per device. The variations were traced to the sensitivity of the JFET first-stage output structure to small misalignments of the mask during the wafer fabrication; in these first two generations of devices, the upper and lower halves of the layout were created by rotating one half of the layout by 180 degrees, but this led to minor misalignments that affected the performance. The team also made other changes to the planar JFET output structure to reduce noise due to feed-through of the reset signal. Testing of these second-generation devices in a wavefront sensor camera at the US Air Force Starfire Optical Range (SOR) 3.5-meter telescope also found significant non-linearities due to a fabrication error that resulted in the misplacement (on the surface rather than buried) of the reset gate transistor. Notwithstanding these issues, the quantum efficiency of these devices was found to be quite good, with a peak of 95% at 750 nm. With appropriate modifications to the readout system voltages the non-linearities were corrected, and the devices are in use on the SOR AO system and in the wavefront sensor for the Gemini Planet Imager. For the third generation of these devices, the planned 160 x 160-pixel format incorporated all of the lessons learned in the first two generations, resulting in devices with fast readout, low readout noise, and reduced variability among the outputs. These devices passed operability testing and were being packaged and prepared for testing in deployed wavefront sensors as the project closed.

Development of the polar-coordinate detectors proceeded through only one device generation because of the considerably longer design development required. In particular, the readout architecture was very challenging because this detector format consists of many isolated islands of pixel blocks, most of them far from an edge of the device, in contrast to the standard CCD layout where the pixels form a continuous checkerboard across the entire device from edge to edge. The team found the optimum solution to be use of long, serial registers, each connecting together a number of subapertures, with each register having enough pixels to hold all of the image pixels from each connected subaperture. Compared to a multiplexing design with a video readout amplifier in each subaperture, the 'snaked' serial registers reduced readout times by at least 20%, offered the possibility of lower readout noise, and reduced concerns about power dissipation and hot spots on the detector. The first prototype versions of this detector were delivered in the fall of 2011. Testing of the frontside-illuminated versions showed excellent charge transfer efficiency and very good readout noise. A design defect in the clocks of one ring of subapertures prevented full operational testing, but the results demonstrated that the polar-coordinate concept is viable as a means of addressing LGS spot elongation.

3. Sub-award C30003T, Lawrence Livermore National Laboratory; 'Pulsed Fiber Laser for Guide Stars.'

Findings: The integrated system achieved its goal of producing 10 Watts of output power in the desired pulse format at 598 nm. The beam quality appears to be good enough for use in a laser guide star system. The system operated for several hours without incident or loss of power.
However, it was found that the system needs approximately 1.5 times as much 938-nm power as 1583-nm power in order to achieve the correct photon balance for 589-nm generation in the sum-frequency mixing crystal. Output power was therefore limited entirely (in this system) by the available power at 938 nm; to achieve higher output power levels would require a more powerful 938-nm input subsystem.

4. Sub-Award C33004T, 'Development of Large Deformable Mirrors Based on Dense Actuation of Nano-Laminate Membranes,' Lawrence Livermore National Laboratory.
Findings: The team reports several findings from the process of producing the NL foils. First, internal stresses in the substrate used during vacuum deposition must be reduced as much as possible. Second, the substrate must be preheated to the temperature reached during deposition before deposition begins, so as to reduce the thermal stresses within the foil. Third, laser cutting of the foils with a short (femto-second) pulse laser is the only method that does not introduce unacceptable curling at the cut edges. The team apparently never succeeded in bonding an NL foil to a MEMS device. First, the team found that the process of applying bonding bumps to the NL foil introduced unacceptable additional curvature to the foil. This was resolved by electroplating the bumps onto the foil before dicing the foil to size from the master sheet. Second, the team found (through a failure of the first attempt) that the amount of force applied in bonding must be carefully regulated to avoid destroying the MEMS device. Reports from the team do not indicate results of any subsequent bonding attempts or the completed production of either first- or second-generation mirrors as planned.

5. Sub-Award C33005T, 'Compact Modular Scalable Versatile LGS Architecture for 8?100 m Telescopes,' Coherent Technology, Inc. (later Lockheed Martin Coherent Technology).
Findings: The team found that beam quality and beam uniformity issues are critical to achieving efficient production of 589-nm output light. At the conclusion of Phase 1, the team generated input powers of 22.8 Watts at 1319 nm and 16.3 Watts at 1064 nm, but achieved only 5.0 Watts of output at 589 nm, short of the Phase 1 goal of 10 Watts. Steps taken during Phase 2 resulted in measured input powers of 98 Watts at 1064 nm and 39 Watts at 1319 nm. Modeling predicted a 589-nm output power of 33 Watts using these inputs. In general, the team found that steps taken during Phase 2 did successfully address the identified problems and should have produced a suitable prototype laser. Unfortunately, the 1319-nm subsystem failed just before final testing of the output power, due to back-reflection of laser light into the originating 1319-nm master oscillator, which damaged that unit. The final test was never completed.

Findings: (1) The wavefront reconstruction step dominates the computing time required on the dedicated processors. (2) All three algorithms can meet the basic requirements for AO correction on a 30-meter-class telescope, but the ONT algorithm has the most potential as a growth path to larger numbers of subapertures because it is the closest of the three to having its required computational steps scale as the number of subapertures (as opposed to scaling as the number squared). (3) The MC-PCG algorithm requires the most on-device random-access memory of the three algorithms, making it problematic for future growth to larger numbers of subapertures.

Training and Development
All of the organizational partners gained substantial experience in the new technology areas they investigated. For more details, see the specific reports by sub-award in the 'Findings' section above.

In sub-award C33002T, 'Development of the Next Generation of Optical Detectors for Wavefront Sensing,' a post-baccalaureate student, Oscar Azucena, was employed full time for 10 months as a research associate at the Center for Adaptive Optics to work on the development of simulations critical to the design of the polar-coordinate detector. A publication resulted from this work (Adkins et al. 2006) and Oscar subsequently went on to enter the graduate program in engineering at the University of California, Santa Cruz.

Paths for fruitful further investigations were clearly identified in the reports from each partner, and several of them, most notably Lawrence Livermore National Laboratory and the California Association for Research in Astronomy, are actively working to pursue those further investigations and find ways to deploy them on telescope facilities to which they have access (Lick Observatory and the W.M. Keck Observatory, respectively).

**Training and Development:**
Not applicable.

**Outreach Activities:**
Not applicable.

**Journal Publications**
**Books or Other One-time Publications**

**Web/Internet Site**

URL(s):
http://www.noao.edu

Description:

**Other Specific Products**

**Contributions within Discipline:**
AODP significantly enlarged the understanding within the astronomical community about leading technologies that can provide the improved AO performance needed for future scientific breakthroughs. AODP was specifically designed to foster development of ideas that entailed significant technological risk. It is to be expected that some of the sub-awards would not result in useable products. The success of the program is judged rather by the lessons learned that will guide future developments. The technological improvements studied under AODP covered three general areas: (1) detectors for high-performance wavefront sensing, (2) powerful and adaptable lasers for generating artificial stars in different formats (for different types of atmospheric compensation), and (3) high-speed algorithms and processing for linking signals from guide stars or laser spots to the corrections that must be applied through the deformable mirror(s). All of the new technologies studied under the AODP award could not have been explored without support from the AODP award funding; they are not yet developed enough for direct application in an existing AO system (so they could not have been funded as part of an upgrade project), and they are too specialized to have any commercial or other non-astronomical applications. All of them have potentially powerful applications as research tools in future generations of AO systems. The lessons learned through the AODP-funded work will guide the future work to develop these technologies to the point of readiness for service at a functioning AO observatory. The most immediate applications will come in two ways. First, future upgrades of wavefront sensing detectors on existing AO systems, or wavefront sensors already incorporated into soon-to-be-delivered systems such as the Gemini Planet Imager, could make, and are making, direct use of high-speed, low-noise detectors developed through sub-award C33002T. Second, lessons learned by the sub-awardee on sub-award C33004T were applied to the development of other 589-nm lasers built by the same company; two of those lasers are now deployed at observatories, one at Gemini South and one at the Keck I telescope.

For details of the specific developments and further work, please see the 'Findings' section above.

**Contributions to Other Disciplines:**
The detector technologies explored under sub-award C33001T also have application in other fields of radiation sensing, including infrared (IR), ultraviolet (UV), and neutron detection. Several of the papers listed under the section 'Journal Publications' above describe those applications. Those technologies are therefore capable of providing new research tools in areas involving UV or IR spectroscopy or imaging of neutron scattering distributions.

**Contributions to Human Resource Development:**
Not applicable.

**Contributions to Resources for Research and Education:**
Not applicable.

**Contributions Beyond Science and Engineering:**
Not applicable.

**Conference Proceedings**

**Categories for which nothing is reported:**
Any Journal
JOURNAL PUBLICATIONS


None.

4. Sub-Award C33004T, “Development of Large Deformable Mirrors Based on Dense Actuation of Nano-Laminate Membranes,” Lawrence Livermore National Laboratory.


5. Sub-Award C33005T, “Compact Modular Scalable Versatile LGS Architecture for 8–100 m Telescopes,” Coherent Technology, Inc. (later Lockheed Martin Coherent Technology).
None.

None.

BOOKS OR OTHER ONE-TIME PUBLICATIONS

None.


Adkins, S. “Polar coordinate CCD array for LGS wavefront sensing”, Wavefront Sensing I OSA conference presentation AOTuB1, 2009


4. Sub-Award C33004T, “Development of Large Deformable Mirrors Based on Dense Actuation of Nano-Laminate Membranes,” Lawrence Livermore National Laboratory.
Papavasiliou, A.P., Olivier, S., Barbee, T., Miles, R., Walton, C., Cohn, M., Chang, K.  
“Nanolaminate Deformable Mirrors”, IEEE Optical MEMS, 2006

5. Sub-Award C33005T, “Compact Modular Scalable Versatile LGS Architecture for 8–100 m Telescopes,” Coherent Technology, Inc. (later Lockheed Martin Coherent Technology).  


