Active Correction of Aberrations of Low-Quality Telescope Optics

Relatively inexpensive optical components could be used in free-space optical communications.

NASA's Jet Propulsion Laboratory, Pasadena, California

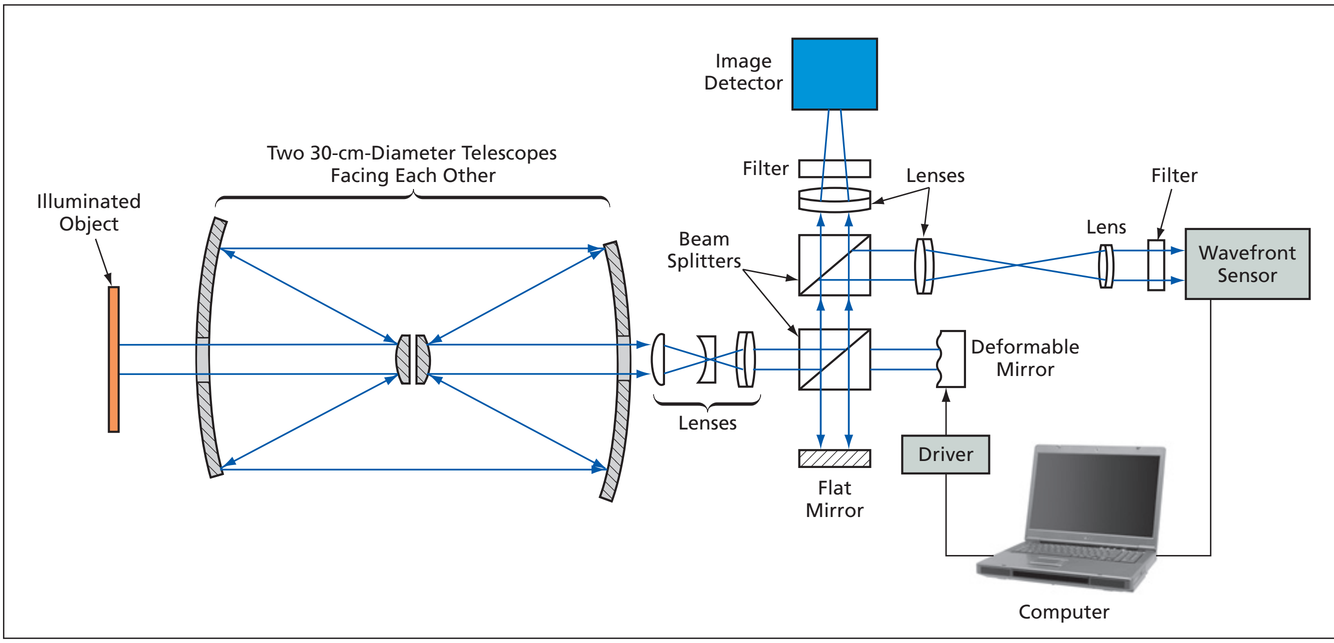

Figure 1. This **Laboratory Apparatus** was used to demonstrate the use of active optics to correct wavefront aberrations introduced by fixed telescope optics.

A system of active optics that includes a wavefront sensor and a deformable mirror has been demonstrated to be an effective means of partly correcting wavefront aberrations introduced by fixed optics (lenses and mirrors) in telescopes. It is envisioned that after further development, active optics would be used to reduce wavefront aberrations of about one wave or less in telescopes having aperture diameters of the order of meters or tens of meters. Although this remaining amount of aberration would be considered excessive in scientific applications in which diffraction-limited performance is required, it would be acceptable for free-space optical-communication applications at wavelengths of the order of 1 μm.

To prevent misunderstanding, it is important to state the following:

- The technological discipline of active optics, in which the primary or secondary mirror of a telescope is directly and dynamically tilted, distorted, and/or otherwise varied to reduce wavefront aberrations, has existed for decades.
- The term "active optics" does not necessarily mean the same thing as does "adaptive optics," even though active optics and adaptive optics are related. The term "adaptive optics" is often used to refer to wavefront correction at speeds characterized by frequencies ranging up to between hundreds of hertz and several kilohertz — high enough to enable mitigation of adverse effects of fluctuations in atmospheric refraction upon propagation of light beams. The term "active optics" usually appears in reference to wavefront correction at significantly lower speeds, characterized by times ranging from about 1 second to as long as minutes.

Hence, the novelty of the present development lies, not in the basic concept of active or adaptive optics, but in the envisioned application of active optics in conjunction with a deformable mirror to achieve acceptably small wavefront errors in free-space optical communication systems that include multi-meter-diameter telescope mirrors that are relatively inexpensive because their surface figures are characterized

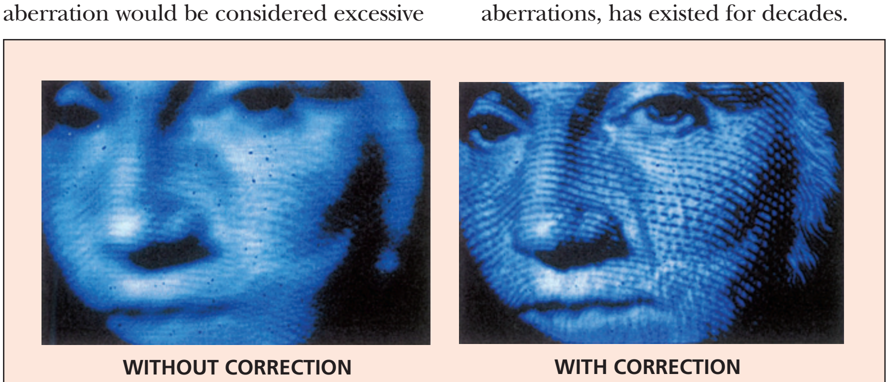

Figure 2. An **Image of Part of a Dollar Bill** was recorded, without and with correction by active optics, in the apparatus of Figure 1.

by errors as large as about 10 waves. Figure 1 schematically depicts the apparatus used in an experiment to demonstrate such an application on a reduced scale involving a 30-cm-diameter aperture. The apparatus included a source of illumination at a wavelength of 1,064 nm; an object to be imaged (an illuminated dollar bill); two 30-cm amateur astronomical telescopes facing each other to emulate far-field imaging; a 19-element thermally actuated deformable mirror at the pupil plane of the receiving telescope; a Hartmann wavefront sensor; an image detector at the receiving-telescope focal plane; associated lenses, filters, beam splitters; and a flat mirror. The output of the wavefront sensor was processed, by a computer, to control signals for the thermal actuators on the deformable mirror. The lenses were chosen and arranged to reduce the diameter of the light beam to the widths of the deformable mirror and the wavefront sensor. The deformable mirror was placed at the pupil plane of the receiving telescope.

The various optics introduced aberrations characterized by, among other parameters, 1.4 wavelengths of root mean square (RMS) wavefront error. Then the closed-loop control system consisting of the wavefront sensor, computer, and deformable-mirror actuators was turned on, thereby reducing the aberrations (see Figure 2) to 0.05 wavelength RMS wavefront error. In addition, the Strehl ratio (the ratio between the peak intensity in the point spread function of an optical system and that of an equivalent diffraction-limited system) was increased from 0.08 percent to 89 percent.

This work was done by Hamid Hemmati and Yijian Chen of Caltech for NASA's Jet Propulsion Laboratory. Further information is contained in a TSP (see page 1). NPO-43173

Dual-Beam Atom Laser Driven by Spinor Dynamics

A Bose-Einstein condensate is adiabatically compressed to drive coherent spin-mixing evolution.

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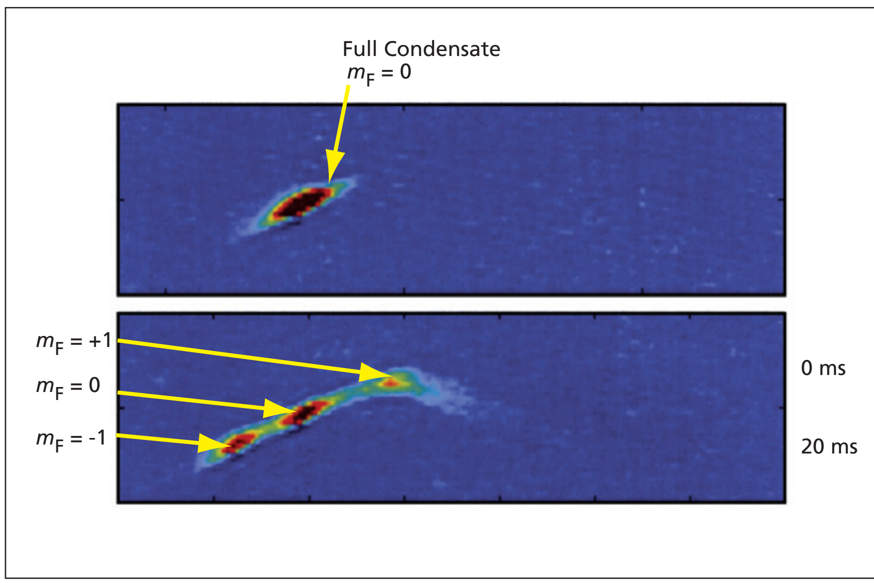
An atom laser now undergoing development simultaneously generates two pulsed beams of correlated ^{87}Rb atoms. (An atom laser is a source of atoms in beams characterized by coherent matter waves, analogous to a conventional laser, which is a source of coherent light waves.) The pumping mechanism of this atom laser is based on spinor dynamics in a Bose-Einstein condensate. By virtue of the angular-momentum conserving collisions that generate the two beams, the number of atoms in one beam is correlated with the number of atoms in the other beam. Such correlations are intimately linked to entanglement and squeezing in atomic ensembles, and atom lasers like this one could be used in exploring related aspects of Bose-Einstein condensates, and as components of future sensors relying on atom interferometry.



A **Bose-Einstein Condensate of ^{87}Rb** atoms is shown at the instant of turning off the optical trap (0 ms) and at an instant 20 ms later. The original field depicted in these images measures 1 by 0.25 mm. Gravitation was directed toward the lower right; the trapping laser beam was aimed toward the upper right.

In this atom-laser apparatus, a Bose-Einstein condensate of about 2×10^6 ^{87}Rb atoms at a temperature of about 120 μK is first formed through all-optical means in a relatively weak single-beam running-wave dipole trap that has been formed by focusing of a CO_2-laser beam. By a technique that is established in the art, the trap is loaded from an ultrahigh-vacuum magneto-optical trap that is, itself, loaded via a cold atomic beam from an upstream two-dimensional magneto-optical trap that resides in a rubidium-vapor cell that is differentially pumped from an adjoining vacuum chamber, wherein are performed scientific observations of the beams ultimately generated by the atom laser.

In the condensate as thus prepared, the atoms are in the magnetic-field-insensitive $m_F = 0$ sublevel of the F = 1 state [where F is the quantum number of total resultant angular momentum (electron spin plus nuclear spin plus electron orbital angular momentum) and m_F is the quantum number of the component of total resultant angular momentum along a physically distinguishable coordinate axis (typically defined by a magnetic field)]. Then the intensity of the trapping laser beam is increased to drive coherent spin-mixing evolution: The increase in the intensity of the trapping laser beam adiabatically compresses the condensate to cause ^{87}Rb atoms to collide and thereby to undergo the angular-momentum-conserving reaction

$$2(m_F = 0) \leftrightarrow (m_F = +1) + (m_F = -1).$$

As a result of this reaction, the original condensate becomes a superposition of (1) equal numbers of atoms in the m_F = +1 and m_F = –1 levels and (2) some