Adaptive Optics in Astronomy

Jay J. McCarthy
NW Computational Intelligence Laboratory
Portland State University

Abstract — The field of adaptive optics (AO) has developed as a means to correct for the phase disturbances of an optical signal by understanding the medium through which it passes. This paper is intended to be a brief introduction to the field of adaptive optics with an emphasis on the role of AO in astronomy.

I. PERPTUAL TREMOR

Since the time of Isaac Newton, it has been known that optical waves (in fact all electro-magnetic waves) passing through the Earth’s atmosphere are subject to tiny disturbance due to the turbulence of the atmosphere. In fact, Newton predicted that the effects of these disturbances would ultimately be the limitation to optical systems for astronomy. In Opticks, Newton wrote [1][2]:

> If the Theory of making Telescopes could at length be fully brought into Practice, yet there would be certain Bounds beyond which Telescopes could not perform. For the Air through which we look upon the Stars, is in perpetual Tremor; as may be seen by the tremulous Motions of Shadows cast from high Towers, and by the twinkling of the fix’d Stars.

The “perpetual Tremor” is in fact the atmospheric disturbances brought on by wind eddies, thermal fluctuations, density differences, and molecular absorption; all of which lead to small changes in the index of refraction. This causes the atmosphere to act as if it were an array of tiny lenses, bending light rays as they pass to an observer on Earth. If we assume that the light from some distance object leaves as a spherical wave front, the waves reaching an observer on Earth would theoretically be plane waves. This turbulence has the effect of changing the phase of a plane wave such that the waves reaching an observer are distorted as shown in Figure 1.

The resolution of an optical system for land based astronomy is primarily limited by the optical elements. The angular resolution of a diffraction limited optical systems is described to be proportional to the frequency and the aperture diameter of the optical elements \( R \sim \lambda/D \). Thus, by increasing the size of the optical elements (increase D) the angular resolution, \( R \), will decrease allowing one to resolve between closely spaced objects. One might naively expect that simply increasing the diameter of the telescope optics (mirrors or lenses) will always increase the resolution. This may be true to an extent, however as the elements allow for higher resolution, a threshold is reached, whereby the resolution becomes more dependent upon atmospheric turbulence. Here, the effects of distortion dominate the resolution power, such that \( R \sim \lambda/r_o \), where \( r_o \) is the Fried’s Coherence Length. This length is essentially a measure of lateral length over which the optical phase distortion is highly correlated and ranges between 5-20cm [3]. Thus, when \( r_o \) is less than the aperture of the telescope, the resolution is no longer diffraction limited, but rather limited by the coherence length.

The role of AO is to develop some knowledge of what distortions have been introduced to the waves due to the atmosphere, such that given this knowledge, the phase distortions can be eliminated. Once these distortions are corrected, the telescope (in theory) can once again become diffraction limited.

II. ADAPTIVE OPTICS SYSTEM

Figure 2 depicts the basic set-up for an AO system. An incoming distorted wave encounters a deformable mirror and reflects a new wavefront, where the phase has been changed due to the shape of the mirror’s surface. The new wave passes through a beam splitter such that part of the wave is received with an imaging device and the remainder is split to a wavefront sensor. The purpose of the wavefront sensor is to reconstruct the phase profile of the wave leaving the deformed mirror, given only its intensity information. Ideally, the wavefront leaving the mirror would be a perfect plane wave, however this is rarely the case. The phase profile information from the sensor is passed to a control system in order to determine the new shape of the mirror which would produce a smaller error (ideally zero) across the phase front. The main point to adaptive optics is that the control system is not only a closed-loop process, but also in real time such that action to the mirror is on the order of 1-1000kHz.

There is a limited variety of sensors used for optical phase distortions. In fact the actual measurement of the phase does not typically involve a phase measurement at all. This is primarily due to the fact that most celestial bodies emit a wide range of frequencies, unlike lasers used for interferometers [3]. Instead, most sensors use intensity information in order to develop local gradients for the phase front. One such measuring...
Figure 2: Basic AO Configuration

device is the Shack-Hartmann Wavefront Sensor shown in Figure 3. This wavefront sensor uses an array of lenses which act as sub-apertures to the incoming, distorted wave. Each lens focuses the light entering the sub-aperture onto a light sensitive device, such as a CCD (charged-coupled device) array. Typical sensors will have an array of 5x5 to 50x50 sub-apertures per sensor operating at megahertz rates [3]. The image of the incoming wave is detected across a CCD array such that if the incoming wave were a plane wave, the intensity would be focused at the center of the CCD. However, if there is a gradient in the phase, the intensity will be shifted in the array as shown in Figure 3. Through a centroid calculation, the local gradient information can be determined, thus allowing for the phase front to be reconstructed. Given the topology of the phase front, the corrections required to be made to the mirror should be intuitive.

The computational expenses for phase front reconstruction are very high, even with the increase in computer performance. Also, for higher order aberrations, current techniques may be limited. Neural Networks have been shown to be quite useful in utilizing intensity information to reconstruct phase profiles [4]. The nonlinear nature of neural networks lend well to the higher order aberration calculations as well as computational efficiency.

Aside from computation, operation of the sensors (here the CCD or other photo-sensitive medium) is limited by the amount of light coming into the telescope. The CCD array is very light sensitive and requires enough incoming light in order to activate and take a measurement. It could also be that the object is bright enough, however we require the maximum amount of light from the object to be transferred to the imaging device, rather than for sensing. Typically, the object that one is observing (such as a galaxy or some other distant celestial body) is so faint that the light from it would not be suitable for use with the sensor. Such is the case for most astronomical viewing applications. In the either case, it is necessary to then find a beacon light source that is within the isoplanatic angle of the object of interest. The isoplanatic angle is a measurement of a plane over which a source of light would undergo the same wavefront error [2]. The isoplanatic angle is typically on the order of several microradians. It is therefore necessary to find a beacon light source that is not only within the isoplanatic angle, but also sufficiently emits enough light to activate the sensor beings used. For instance, suppose the sensitivity of the CCD required 150 photons per sample at a 100Hz sampling rate. It could be calculated that we would require a beacon source (often called guide star) of magnitude, $m_v = 12$. Given that there are $1.45*\exp(0.96*m_v)$ stars/rad², we can conclude that we have 150,000 stars/rad² to choose as guide stars. If the isoplanatic angle is 10µrad (as it is at Keck in Hawaii), there would be approximately 1.46x10⁻⁷ stars/µrad², essentially zero, for any particular object of interest [2]. Though it may initially appear hopeless to find a guide star near an object we wish to view, a simple method of producing artificial beacons, or laser guide stars, has overcome this problem.

Laser guide stars (LGS), or laser beacons, were developed as a means to produce bright objects within the isoplanatic angle. Once the artificial star has been produced, the light reaching the telescope from the LGS and the object of interest will have roughly the same distortion due to the atmospheric turbulence. Therefore, the necessary changes to be made to the deformable mirror can be calculated based upon the sensory data for the LGS (which will be inherently much brighter than the scientific object). Figure 4 shows, conceptually, how a LGS can be implemented. It is obvious that there will be additional errors introduced by using a LGS due to the cone effect (focal isoplanatism) since the LGS is relatively close to the telescope (compared with the scientific object). Thus, turbulences occurring above the LGS and outside of the cone will not be accounted for in this methodology.

Figure 3: Concept of Shack-Harmann Sensor.

Figure 4: Cone Effect for Laser Guide Stars
There are two types of designs for producing laser guide stars: Rayleigh scattering and sodium resonant backscattering. Rayleigh scattering is ideal in the UV to 600nm wavelengths and have been implemented using Nd:YAG, copper vapor, and excimer lasers [3]. These types of LGS utilize the scattering effects of the atmosphere to produce artificial stars at altitudes from 5 - 20km. Rayleigh scattering LGS are sufficient for smaller telescopes (D < 2m), however since the effects of higher atmospheric turbulence are not accounted for, other designs are required for larger telescopes.

The fact that there exists alkali metals in the mesosphere lends to the potential for resonance fluorescence. In fact, at around 92km, a sodium layer exists such that, when excited by a laser tuned to 589nm, will create a LGS [3]. This much higher altitude incorporates more of the atmospheric turbulence information compared to Rayleigh scattering and opens up the viewing cone as shown in Figure 4. Also, since the laser is tuned to a tight line, the efficiency of the LGS light is higher compared to Rayleigh scattering. Figure 5 shows the Lick Observatory atop of Mt. Hamilton in California creating a LGS for a 3 meter telescope.

The goal of the deformable mirror is to reproduce the phase conjugate of the incoming wave in order to reflect a plane wave. There are a variety of different forms of deformable mirrors used in adaptive optics. These include (but not limited to) segmented mirrors, thin-film membranes, and piezoelectric mirrors. Each of these can use a different set of actuators to control the surface topology of the mirror. For instance, Figure 6 shows a comparison to a discrete actuator design and a bimorph structure, such that two dissimilar materials are used in construction. These materials are such that their responses to temperature or voltages are different. In this method, local control of the surface can be achieved by using the mirror as an actuator compared to using discrete actuators to move mirror segments. The total number of individual actuators for a deformable mirror can be on the order of a few thousand per mirror [3].

The final segment to developing an AO system is integrating the wavefront sensory data with the deformable mirror actuators. The control strategies are typically closed-loop controllers (similar to Figure 2) such that the feedback from the sensors occurs after the optical signal has reflected from the mirror. The control mechanism for this task is not only highly complex (controlling several thousand actuators a millisecond

**III. CONCLUSIONS**

Once all of the AO pieces are put into place, one can achieve a much higher resolution for imaging of astronomical objects. Figure 7 shows a comparison of two images of Galaxy NGC 7469 with and without adaptive optics. Adaptive optics techniques are not limited only to astronomy, but can be used for medical imaging, telecommunications, and vision science. The introduction of AO has rejuvenated land based astronomy. Most observatories using 4m telescopes or larger are retrofitting their optics with AO hardware to improve and extend the imaging capabilities of their current systems. Although space bound imaging devices will nearly always outperform any land based instrument, the trade-off in costs needs to be taken into account. The cost of fitting a current instrument with AO components is far more economic than launching a telescope into space (not to mention repair costs). Until those costs are brought down, the field of adaptive optics will continue to provide a rich area of research interest and new business opportunities.
REFERENCES


Images for this paper taken from the following websites:

http://cfao.ucolick.org/ao/why.php
http://www.adass.org/adass/proceedings/adass99/O4-01/