1.6 Beam Wander vs. Image Jitter

It is common at this point to look at beam wander and image jitter and ask what differentiates them. Consider a cooperative optical communication system that has a separated, unconnected transmitter and receiver. The transmitter used to propagate the beam can be affected by vibration and the effects of the atmosphere such that the beam can wander over the surface of the receiver. The receiver can also be affected by local vibrations as well as the effects of beam wander, which will change the angle of arrival of the wavefront from the transmitted beam.

One goal of the designer of an optical communications system is to reduce the effects of beam wander and image jitter on the receiver. This is also true for imaging systems that acquire and image an object, and continues to follow or track the object while obtaining a high-quality image. In order to achieve these goals, scientists need the ability to cover a large range of angles and hold this to a high level of precision. This naturally breaks into two distinct categories of angular control: one related to steering, the other to stabilization.

In a transmitter and receiver system, the objective is to get the information from the transmitter into the receiver as effectively as possible. This goal becomes significantly more difficult to meet when the transmitter, receiver, and the propagation medium are all in motion. This is further complicated when the information transferred must be kept private. In this case, there are significant advantages for the transmitter to incorporate techniques for keepping the beam on the receiver and for the receiver to acquire as much of the signal as possible onto its detector. Ideally, they will work cooperatively to support the need for a private transmission.

The importance of image stabilization has long been recognized in astronomy, particularly with the use of large telescopes. The problem for astronomers is that the objects in the sky (the transmitters) are not really directed at the receiver. In this case, the tracking and pointing of the telescope mount serves to provide coverage over the range of the whole sky and acts to provide a level of beam steering. However, the starlight passing through the atmosphere jitters under turbulence, causing the image to wander. Astronomers then rely on image stabilization to control the image position in the focal plane to within a few tens of microns. One advantage of image-stabilization systems on telescopes is that they also correct for the effects of a poor tracking mount; i.e., beam wander that is introduced by the telescope mount.

Nearly all modern, professional telescopes incorporate some form of image stabilization in the camera system. The same concept has been extended to advanced telescopes in order to correct for more than image motion, actually correcting for the dynamic diffractive effects of the earth's atmosphere over very small scales. Such systems are known as adaptive optics systems.

The need for beam steering and image stabilization is, of course, not limited to astronomical and communications systems. Both the commercial and defense establishments are incorporating these concepts. Some examples are in the commercial market such as image-stabilized binoculars and video cameras, while laser

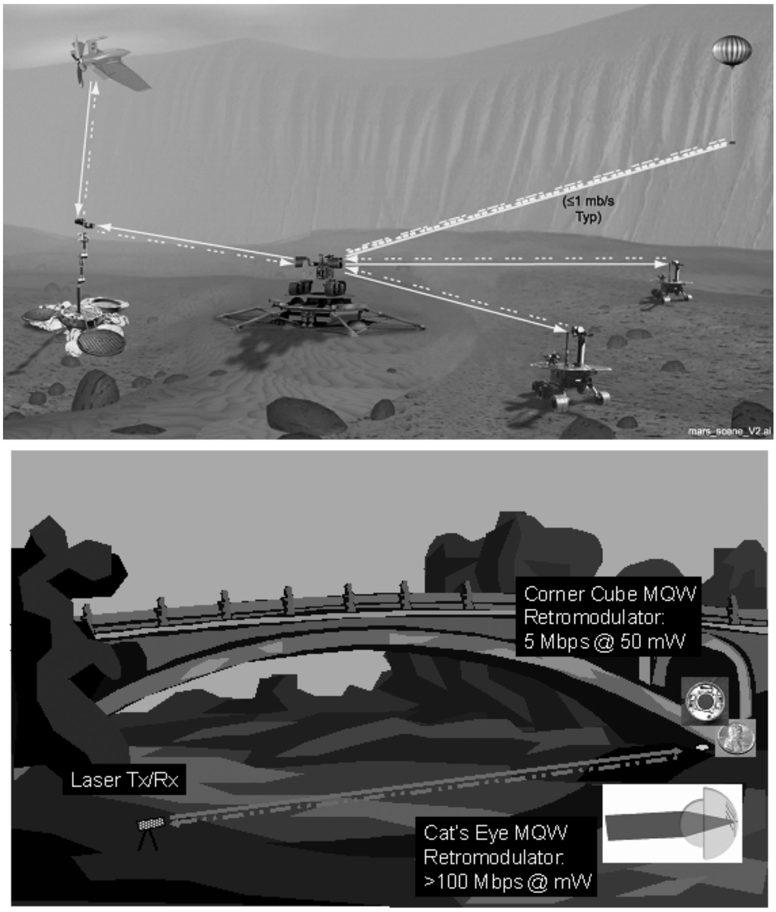

Figure 1.6 Illustration of a complex optical communication system based on a multiple quantum well receiver/retroreflector used for military applications. (Image courtesy of U.S. Naval Research Laboratory.)

light shows rely on advanced beam-steering technology to attain spectacular visual effects. Laser communication is an example of a technology that is of interest to both the commercial and defense arenas.

2.4 Angle of Arrival Fluctuations

A beam of light passing at an angle though the atmosphere arrives at the earth's surface displaced from its original path. In addition, the beam continues to move or oscillate about some point because of the effects of turbulence or mixing in the atmosphere. This creates fluctuations in the index of refraction which both evolve and move across the beam over time. As a result of these turbulence fluctuations, the beam wanders over the surface about a central point.

In the case in which a beam overfills the receiver, the effect of beam wander introduces small changes in the angle of the wavefront to the aperture or its optical axis as shown in Fig. 2.5.

A wavefront passing through the atmosphere can be thought of as a large number of narrow beams of light that were in phase before entering the atmosphere. The

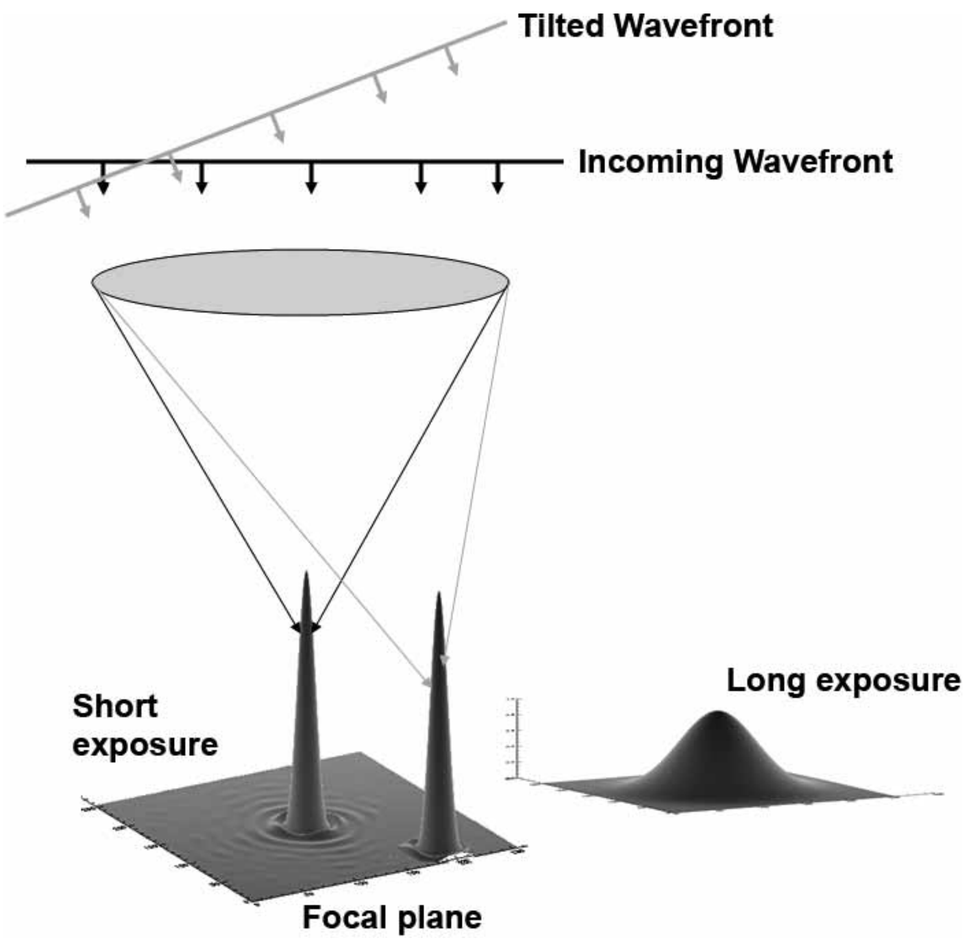

Figure 2.5 A tilted wavefront results in the displacement of the focus point in the focal plane. Over time, the long-exposure profile is generated.

size of the turbulent atmospheric cells determine the effect the atmosphere has on the phase and direction of individual beams. The points of common phase in the beam denote a wavefront, and on passing through the atmosphere their phases shift. The wavefront shows more structure and the overall shape is no longer planar. Thus a wavefront whose outer extent is defined by the aperture of a telescope can have a very different shape on one side of the aperture compared to the other because of the changes induced by atmospheric turbulence. Conversely, if the telescope aperture is smaller than the size of the turbulence cells, the effect of atmospheric turbulence is considerably reduced over the aperture.

When analyzing turbulence, an important parameter is the effective size of the turbulence cells, usually denoted as r_0 or the Fried parameter (Fried 1965), compared to the aperture diameter denoted by D. Thus the ratio D/r_0 (Hardy 1998) is the crucial relationship in determining whether significant improvements in image quality will be achieved by compensating image motion. The effect will be significant for $1 \leq D/r_0 \leq 10$. This effect is illustrated in Fig. 2.6.

When the turbulence cells are large compared to the aperture, the effect is to change the angle of the wavefront to the optical axis of the telescope, and there is

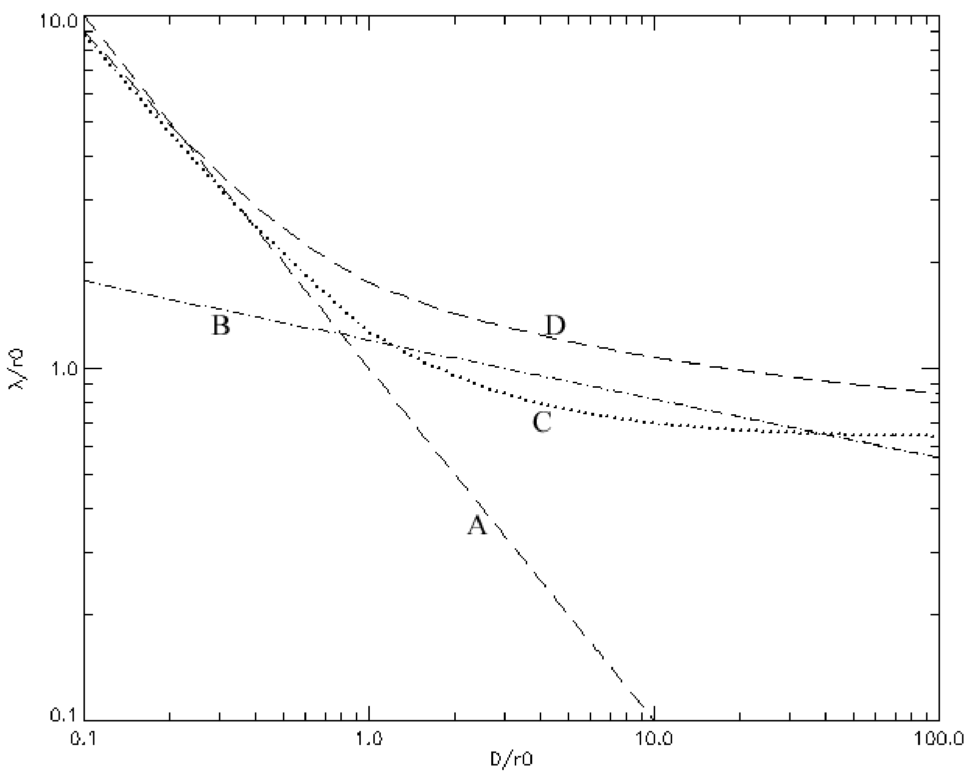

Figure 2.6 Resolution of an uncompensated telescope as a function of D/r_0. The plots are normalized λ/r_0. Curve A is the diffraction limit; B is the effect of jitter; C and D are the short- and long-exposure resolutions.

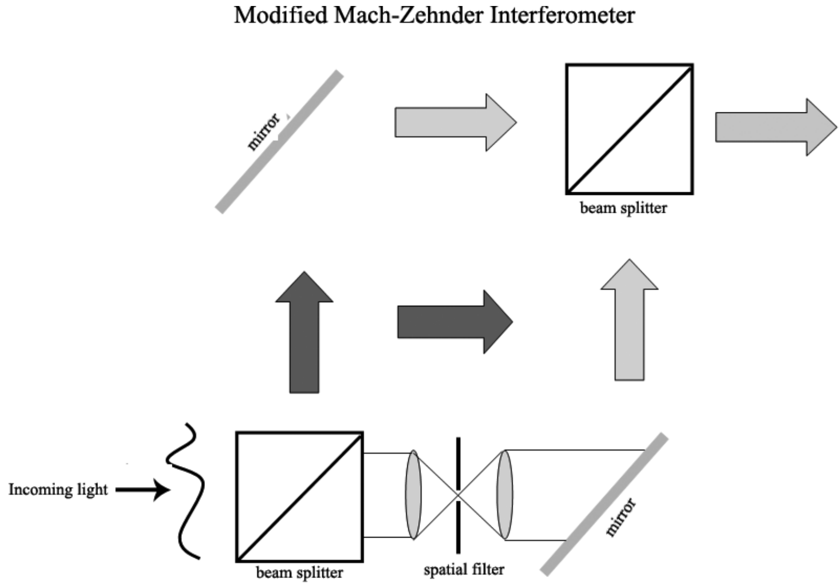

Figure 3.7 Mach-Zehnder interferometer modified to function as a wavefront sensor. The reference beam is generated using a spatial filter. The transmission versus reflectivity of the beamsplitter cubes must be chosen to maximize the fringe contrast.

3.3.2 Shearing interferometer

One of the simplest interferometers to construct is the shearing interferometer. The basic approach is to take a single wavefront and split it into two beams, which can then be displaced by some fraction of the wavefront diameter and overlapped, or sheared. Interference occurs in the sheared beams with respect to the displacement, and observable fringes are formed in the overlap area. The shearing interferometer is an indirect wavefront sensor as it measures the difference in the aberrated wavefront compared with it, but displaced by a fixed amount. Shearing interferometers operate by making comparisons in the direction of shear only. A second shearing interferometer is needed, rotated 90 deg, to get information in the orthogonal direction.

A simple shearing interferometer can be constructed using a single plate of glass, such as a microscope slide, and reflecting a collimated laser beam off it at an angle. The optical path difference between light reflecting from the front and back surfaces of the lens is naturally displaced, or sheared, by the time it strikes a screen some distance away. The reflections from the front and back surfaces, shifted and overlapped on a screen show fringes, which reveal the aberrations in the microscope slide. Figure 3.8 illustrates a simple shearing interferometer showing the aberration in a thin glass plate such as a microscope slide.

Interferometers have many variations and are usually selected to support the measurement of optical-path-length difference based on the specific application.

4.4 Use of Tip-Tilt Correction with Laser Guide Stars

Several advanced laser guide star systems use an artificial star projected high in the atmosphere. These systems eliminate the need for a bright reference star to sample the atmosphere; however, there is still a need for a reference star. A natural guide star is still required to stabilize the systems to the star field. This requires only a low-order image-stabilization system, so a significantly fainter star than is needed for high-order correction can be used, allowing more of the sky to be imaged. The configuration of the laser-guide star system is shown in Fig. 4.6.

4.5 Mechanical Operation of Tip-Tilt Stages

Tip-tilt stages, often called steering mirrors, are made by several manufacturers and come with a wide range of features that improve the mirror's open and closed loop performance. Mirrors that use actuators based on piezo materials have distinct performance differences as compared to mirrors that use voice-coil or audio-speaker actuators.

Piezo actuators are made from plumbum zirconate titanate (PZT), a polycrystalline ceramic that changes length with applied voltage. These actuators, fitted to a platform, provide deflection that can be controlled.

Voice-coil actuators (or, more commonly, audio speakers) are electromagnetic coils that move in a magnetic field. By applying a current to the electromagnet, the

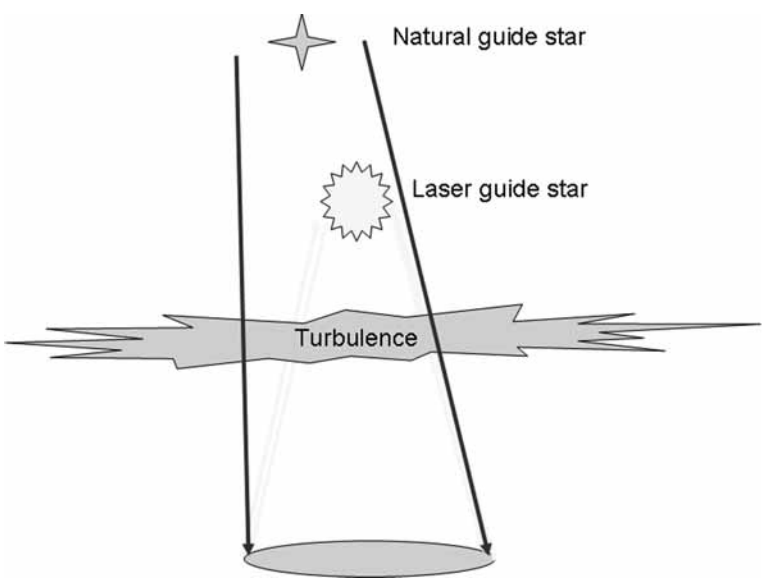

Figure 4.6 Laser-guide stars require a natural guide star to provide tip-tilt correction. The artificially generated star is projected above the turbulence layer and must be close to the position in the sky of the natural star for good correction.

speaker cone is displaced; when the current is removed, the speaker cone is pulled back to the rest position.

Both of these systems have poor open loop performance; that is, they have considerable amounts of overshoot when powered. As a result, sophisticated feed-forward systems are needed to idealize the actuator behavior. Once this idealized behavior is achieved, both systems have excellent performance.

5.3 System Control

The optical layout shown in Fig. 5.1 requires an additional component to function: a controller that takes information from the optical sensor and converts the signal into a correction to the position of the tip-tilt mirror. As such, the controller must be able to "read in" the voltages from the sensor that define the position of the star on the sensor, and write to the tip-tilt mirror the movement that keep the star at the desired position. This requires the control system to take the detected motion from the sensor and convert it to the correct amount of motion in the compensator.

The controller's ability to function correctly requires good calibration of the range of motion of the compensation device and how that range maps onto the active area of the sensor. This calibration map can be created by using the tip-tilt mirror to move a spot of light over the sensor, recording the voltages on the mirror and the voltages from the sensor. Ideally, the result is a linear relationship between the two devices. When properly calibrated, the result is an equation that maps the position of the light on the sensor to the voltage on the mirror (a proportional control scheme):

$$V_x = \frac{B}{A} S_x \, , \tag{5.1}$$

where V is the voltage applied to the compensation mirror, and the ratio of B to A scales the applied voltage to the mirror to the location of the spot on the sensor.

This astronomical image-stabilization system is designed so that the reference point for stabilization is wherever the light lands on the sensor. This is often better than defining a specific point, such as the center of the sensor, as the reference, because it requires less effort to set up the system. It is important to place the mirror in a neutral position, with an even amount of throw in all directions, so that the maximum angular throw is available to keep the image on the camera. Similarly, care must be taken so that the location of the image on the sensor is not too close to the edge of the sensor or, if there is a large excursion in the position of the star image, it could fall off the edge of the sensor. To prevent the image of the star from being too close to the edge of the sensor or, during operation, having the mirror close to its limits, an automated approach is commonly used to signal the telescope mount to reposition itself to a more favorable orientation.

With the control system operating, the image-stabilization system detects and responds to motion of the spot on the sensor, and uses the tip-tilt mirror to drive the spot back to the reference point. An integrating camera records the motion of the spot, but since the excursions away from the stabilization position are kept to a minimum, most of the time the spot remains on target. As a result, the intensity of the peak and the resolution of the image are improved. The next section builds on these concepts to produce a simple working image-stabilization system.