MEASUREMENT OF TELESCOPE SYSTEM ABERRATIONS

Raymond N. Smartt
National Solar Observatory/Sacramento Peak
National Optical Astronomy Observatories
Sunspot, NM 88349

Abstract

Wavefront error measurement of large optical systems is important in many applications. Such measurements can be accomplished by a wide variety of tests. It is shown that interferometric tests have the advantage of providing direct quantitative data, but that of the wide range of two-beam interferometer systems, few prove to be practicable for in situ measurements of large optical systems. For this class of measurement, the Point-Diffraction Interferometer (PDI), which forms a reference wavefront directly from the image of a point source, is especially useful. The general characteristics of this interferometer are presented and applications illustrated by several examples.

1. Introduction

To optimize the performance of telescope systems, wavefront errors of the optical system should be minimized. Adaptive Optics (AO) can in principle be used to correct the dynamic wavefront error due to the earth's atmosphere, local effects associated with the dome, as well as any systematic telescope errors. However, at best this is likely to be an imperfect compensation, especially if the errors are not small, but rather of the order of a wavelength or more. Higher order telescope aberrations might well prove impossible to compensate properly, except with an extremely advanced AO system. For example, since the atmospheric wavefront does not contain much 7th order spherical aberration, AO mirrors are typically not designed to remove it. In any case, residual errors in the analyzing instrumentation might not be included in the optical path of the AO input. Hence, measurement, and minimization, of the fixed wavefront error of the total optical system can be essential to have any realistic prospect of obtaining an overall operating performance close to the diffraction limit. It should be noted however that errors that arise in the atmospheric path to the telescope might in a random way occasionally substantially compensate the systematic errors of the optical system itself, even if complex.

2. Telescope Tests: Screens

Of the large range of optical tests available to determine the system aberrations (Malacara 1978), few are convenient, or even practicable, for testing large systems in

†Operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.
situ, such as large astronomical telescopes and their ancillary optical systems. In a special adaptation of the Foucault test (Darvann and Dunn, 1986), a solar telescope can be tested using the sun as a source, even under poor seeing conditions. An image of the sun is blocked by a knife-edge except for a small strip of the limb. Integration of the image of the pupil over a period of 30 s reveals the Foucault pattern corresponding to the telescope aberrations. Disadvantages are that quantitative data are not easily extracted and localized defects in the pupil can be smeared or, under certain circumstances, will not register at all. Nevertheless, under ideal conditions the Foucault test is extraordinarily sensitive and can reveal errors < 1/100 (Texereau, 1957).

Other tests such as the "wire" test, and variants of it, are also useful, especially for direct tests of aspherics (Meinel and Meinel, 1989). Quantitative measurement of geometrical errors of large objective mirrors can be obtained by placing an opaque screen containing a uniform array of holes over the mirror surface, the Hartmann test, and analyzing the corresponding spot diagrams in the image. This test can be performed on a total telescope system with a star as source. Perhaps more practical and generally useful is the Ronchi test in which a ruling, consisting of opaque and clear lines of equal width, is placed at the image of a point or slit source as formed by the system under test. In the case of a coarse ruling, the modulated image can be accurately described on the basis of geometrical optics. For a fine ruling (grating), diffraction and interference dominate and interpretation then must be treated in the context of physical optics. In any case, the shape of the Ronchi "fringes" is not directly related to the shape of the surface (or wavefront), but rather to the transverse aberration function.

Each of these tests will find its optimum applications(s), as determined by the conditions of the test configuration and measurement requirements. However, as will be shown below, some two-beam interferometers constitute superior test devices for certain telescope testing applications.

3. Telescope Tests: Interferometric

Two-beam interferometer tests have the attraction of providing quantitative data directly from the interferogram. Except in the case of the shear-type interferometers, the shape of the interference pattern provides direct mapping of the wavefront error across the pupil. From a good-quality interferogram, the error can be determined point by point in the pupil with a precision of, say, \( \lambda /10 \), and, using special techniques, one to two orders of magnitude better. From the interferogram, aberration coefficients, the MTF, the Strehl ratio, and other parameters of the system under test, can be routinely derived. However, most interferometer tests are practicable only under conditions of an extremely stable air path and minimal mechanical vibration. These requirements usually translate into short air paths and the total system mounted on an anti-vibration table. Otherwise, fringe excursions can be so large (much greater than one order) and so rapid that the interference pattern completely disappears.

3.1 Classification of two-beam interferometer types

A large number of two-beam interferometers have been described, but most are variants of only a few fundamentally different types. In almost all cases, the light from a point source is first divided into two beams to produce a "test" and a "reference" beam prior to entering the system under test. These two beams follow separate paths, or at least have different geometries, such that the test beam has impressed on it any phase variations caused by the system under test, while the reference beam is unmodified.
The interference fringe pattern shows the variation of these difference across the pupil as variations in fringe position, in terms of the wavelength of the light used.

One classification can be made according to the process of generating two beams. In the Michelson interferometer, one beamsplitter serves both to divide and to recombine the beams, while in the Mach-Zehnder interferometer, two are used. Beaumsplitters of other types, such as those that separate by means of polarization, scattering (as in the scatter-plate interferometer (Burch, 1962)), and diffraction are also used. Several two-beam interferometers operate by the interference between a direct and a diffracted beam. For example, the diffracted component may be derived from a linear diffraction grating, as used in one form of the Twyman-Green interferometer, from a circular grating as in the Zone-Plate interferometer (Smartt, 1974), or from a complex diffraction screen in a holographic interferometer. Beaumsplitting by diffraction can have several advantages. For example, a zone plate need not have high substrate quality since both reference and test wavefronts are equally affected. Also, extremely simple systems can be devised.

Another classification can be made on the basis of the configuration of the two beams. One such class is where the reference and test beams have equal paths along a common axis. For such common-path interferometers, such as the scatter-plate, Dyson (Dyson, 1963), and zone-plate interferometers, the effects of vibration and air turbulence are far less than for interferometers in which the beams follow separate (and often unequal) paths. Furthermore, since the paths are equal along the optical axis, a white-light source can be used, of special advantage in certain applications. Most common-path interferometers must be used in auto-collimation, requiring a full-aperture reference flat.

We point out a further classification. As mentioned above, most two-beam interferometers operate by first forming a reference and a test beam prior to light entering the system under test. The configuration is such that the reference beam does not pass through the system under test, or if it does, as an unexpanded, or focused beam. Hence, it is unaffected by the system aberrations. But there are other interferometers in which the light is divided into a test and a reference beam, after passing through the system under test. This allows the enormous freedom of testing entire optical systems, in situ, without the need to fulfill some special interferometer configuration. Large telescope systems can then be tested in single pass with a remote source, avoiding the need for a large reference flat. Three examples are the lateral-shear, radial-shear and point-diffraction interferometers. The lateral-shear interferometer is simple to align and use (Saunders, 1975), a distinct advantage for tests carried out in the field. The interference pattern, however, does not give the wave-aberration directly, but its gradient (for small shears), and requires computer reduction for all but the simplest cases. Moreover, in its usual form, it cannot be used with white light, virtually precluding the use of a star as source. The radial-shear interferometer can also be made in a compact and simple form (Smartt, 1974, 1985), but cannot be used for example to test a telescope in which the aperture has a central obscuration. Further, the interference pattern shows the true wave aberration only if the central part of the pupil contains a negligible error (a reasonable approximation in many cases). The point-diffraction interferometer (PDI) does not suffer from any of these shortcomings, and has the advantages of the diffracted-reference-beam designs as well as those of common-path interferometers. The PDI in its simple form does have a limitation on the number of "tilt" fringes that can be added to the interference pattern, but this is normally not a problem. While many fringe analysis programs require a large tilt (30 or 40 fringes), others work well with closed fringes (defocus). Hence the PDI is regarded as an attractive, simple method to test large, complex systems, especially
where there is little or no control over environmental circumstances. Aberrations introduced by operating the telescope at finite conjugates may be removed in the fringe analysis program.

In summary, it is sometimes possible to test large optical systems in autocollimation. For this, common-path interferometers are generally well-suited. But sometimes it is required, or at least more convenient, to test in a single-pass mode with a remote source. For both configurations the PDI proves to be a singularly useful test device, which results from the generation of a reference beam by point-diffraction, its common-path properties, and the ability to generate an interference pattern simply by insertion at any image plane.

### 3.2 Characteristics of the point-diffraction interferometer

The PDI has been widely discussed in the literature (see, for example, references in Smartt, 1984). The theory has been developed in some detail (Smartt and Steel, 1975; Malacara, 1978; Smartt, 1984). The PDI has been used in a wide range of applications (see, for example, Geary, 1987; Gigho, 1988) and these include measurements of astronomical optical telescopes (Smartt, 1979; Engvold et al, 1983; Delvo, 1985), periscopes (Houston, 1982) and a mm-wave radio telescope. The general utility of the PDI derives from the simplicity of its operation. Fringes are formed simply by locating it at the image of a point source. In its common form, it consists simply of a clear aperture (or opaque or reflecting disk in a partially transmitting (or clear) surround. Incident light is transmitted through the film (and aperture) with reduced amplitude, while the excess light transmitted by the aperture is diffracted. Provided the aperture is circular and sufficiently small relative to the image spread, the diffracted component is spherical. This reference wavefront interferes with the undiffracted wavefront and the resultant interference pattern represents an accurate and direct measure of the wavefront aberration. A white-light (star) source can be used, but a laser is extremely convenient. The simplicity of the PDI avoids the usual problems of other interferometers where the interference pattern, using a laser, is often severely degraded by the multiple interference that occurs between the multiply-reflected, diffracted and scattered components. Moreover, high-visibility fringes can be obtained by appropriate choice of aperture size and interferometer setting (to balance the amplitudes of the two components) and as a consequence of the fact that the two interfering components have the same polarization state.

### 3.3 Application of the PDI to testing telescope systems

Since the PDI can be inserted at any image plane in an optical system, it can be used to test the corresponding section of the total optical system. For example, if a laser source is focused at the entrance slit of a spectrograph, the aberration contribution of the spectrograph optical system, including the grating itself, can be simply determined by placing the PDI in the plane of the exit slit. Any such auxiliary optical system can be similarly tested. The complex Universal Birefringent Filter (UBF) optical system of NSO/SP has been tested in this way. The filter itself consists of 58 crystal elements and polarizers in series, within an optical system consisting of four compound lenses, four 45 degree prisms, a Fresnel rhomb, a thin-film filter, two external polarizers, two mica waveplates and two KD*P modulators, all in series. Figure 1 is an on-axis interferogram of this total system, obtained simply by focusing a laser source at the entrance field aperture and locating the PDI at the image plane. An off-axis
interferogram is obtained simply by moving the laser away from the optical axis. This filter could have been tested, of course, with preceding optics in the beam, or even the total telescope system itself. If it is not possible or convenient to test a telescope in autocollimation, a low-power laser can be used at a remote location, approximating an infinite conjugate distance. For maximum light economy, the spread of the laser beam at the system under test should not be substantially greater than the telescope entrance aperture; for large distances, an unexpanded laser beam could be suitable -- otherwise a low-power microscope objective should be used. Provided that disturbances in the interference pattern, due to the atmospheric path, are on average less than one wavelength, the wavefront aberration can be precisely determined. This is achieved by recording many interferograms and averaging the cumulative derived wavefront error maps.

A 61-cm aperture Cassegrain telescope has been tested in this way using a 3-mw He-Ne laser set up at a distance of 2.3 km. The Gaussian spread of the raw beam at the telescope was mainly concentrated over an area of 1 m diameter. High-quality interferograms were obtained, with sufficient light to observe the interference pattern projected on the interior of the telescope dome. Figure 2 shows a sample interferogram. The 2.3 km path was within a few meters of the ground over a distance

Figure 2. PDI interferogram of a 61-cm aperture Cassegrain telescope using a 2 - mW He-Ne laser source at 2.3 km. The dominant asymmetrical characteristic of this interferogram reveals a misalignment error between the primary and secondary mirrors. Other non-uniformities are due to thermal fluctuations in the air path during the 1 ms exposure.
of about 0.3 km, limiting the seeing quality. But under extremely quiescent nighttime conditions, fringe displacement due to the effect of the atmospheric path was typically much less than one wavelength. An alternative approach to testing large telescopes, where two telescopes can be pointed at each other, is to use one as a nominal collimator, to provide a source close to infinity. If the two telescopes have close to the same aperture, the emergent beam should be made somewhat divergent so that aberrations of the first telescope contribute minimally to those of the telescope under test.

Finally, as has been pointed out, a white-light (star) source can be used with the PDI. This has been confirmed in tests of a 152-cm Cassegrain telescope using Capella, a zero magnitude star, near zenith as the source. Useful interferograms, somewhat blurred with a 1s exposure photographic recording, were obtained under extraordinarily stable atmospheric conditions.

4. Conclusion

Many optical tests are available that can be used to determine the wavefront aberration of telescope systems, each having advantages for certain test requirements and environmental conditions. Interferometric tests have the general advantage of providing direct quantitative data, but few are suited or even practicable for in situ measurements of large optical systems. If the test can be carried out in auto-collimation, common-path interferometers seem best suited, the choice dependent on detailed considerations of the particular test problem. Of these common-path interferometers, the point-diffraction interferometer emerges as generally the most useful device, especially in single-pass testing of large instruments.

References

Smartt, R. N. and Hariharan, P.: 1985, Optica Acta, 32, 1474
Discussion

S. Koutchmy: The methods you described are excellent for measuring rather large scale effects (aberrations) over the pupil and correspondingly, the alternation produced by the instrument in the high-frequency part of the MTF. Additionally, very small scale effects, up to the "size" of the micro-roughness, are also producing alternations in the low-frequency part. These effects produce a large amount of light outside the image which can be measured (scattered light) and introduced in the analysis.

R. Smartt: Measurement of scattered light due to micro-roughness of optical surfaces is of course important also in assessing properly the overall performance of telescopes or other major optical system, but other periods of tests are required. Apart from direct measurement of scattered light, the Phase contrast test provides useful supplementary data to Point-Diffraction interferograms, and the same test configurations can be used.

O. v.d.Lühe: Could the astigmatism shown for the tower telescope be caused by incomplete cancellation of the astigmatism caused by tilting the primary and the cylinder in the exit window?

R. Smartt: Since I do not have a record of the location of the focal plane for this test, I am unable to determine the contribution of the effect in the interferogram.
SECTION V

HIGH SPATIAL RESOLUTION SPECTROSCOPY

Chair: F. L. Deubner