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Solutions for environmentally robust interferometric optical testing

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ABSTRACT

Optical interferometry is widely used for surface metrology, and phase-shifting interferometry (PSI) remains the "gold standard" for measuring surface form and texture. In the past, the environmental sensitivity of PSI relegated its use to dedicated metrology labs with well-controlled environments. As metrology requirements have expanded beyond the lab, advances in metrology techniques now enable high-precision optical testing in places previously considered inappropriate for interferometric techniques. A class of environmentally-robust methods preserve the gold-standard accuracy of PSI by measuring and accounting for rigid-body motions from vibration and large-scale airflow during the PSI acquisition. These methods, including model-based PSI, use a physical model of the interference to measure cavity rigid body motion and accommodate a wide variety of measurement geometries, surface shapes, surface departure, reflectivities, and environmental conditions without changing the user's measurement process. For more extreme environments, spatial carrier methods analogous to off-axis holography extract the surface phase fast enough to "freeze" vibration and air turbulence in a single camera frame. The price paid for single-frame acquisition is a loss of lateral resolution as well as a modest increase in sensitivity to optical aberrations, requiring calibration for compensation. This paper will describe current techniques and methods, as well as provide examples and results for practical measurement scenarios in the manufacture of high-precision optical components and systems.

Keywords: Interferometry, metrology, vibration, phase-shifting, dynamic, carrier fringe, optical testing

1. INTRODUCTION

Figure 1: (Left) A benchtop laser Fizeau interferometer. (Right) An instrument for measuring large flat optics.

Metrology is defined by the National Institute for Science and Technology as "the science of measurement, embracing both experimental and theoretical determinations at any level of uncertainty in any field of science and technology" and is succinctly expressed with the old adage, "if you can't measure it you can't make it". Laser interferometric metrology is commonly applied to precision measurements of optical wavefronts using interferometric principles. Laser interferometers such as those shown in Figure 1 serve a wide variety of applications in optics manufacturing, characterizing the optical performance of catalog lenses as well as aerospace telescope mirrors, windows and complex optical assemblies, to name just a few. Requirements vary depending on the application, but the goal is usually the same: determine the surface form of an optic or wavefront produced from an optical assembly. Traditionally this would be done in a dedicated lab, but more and more frequently, measurements must be made under less than ideal conditions. This paper discusses the various

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methods available to the metrologist to limit the effects of environmental variations, their advantages and disadvantages, and provides advice for choosing the method best suited for the expected environment and application.

Interferometry is a comparative process, measuring an unknown wavefront by comparing (interfering) it with a known one. In a surface measurement application, for example, a known wavefront is split into two with one wavefront reflected off the surface of interest, imparting the surface topography onto the wavefront phase. The two are then recombined, allowed to interfere and an interferometer is used to recover the optical path (or phase) difference (OPD) experienced between the two wavefronts (modulo 2π). The environment influences the measured OPD through two effects: vibration and turbulence.

Turbulence modifies the refractive index of the air between the test and reference paths, changing the OPD directly. In typical laboratory conditions, turbulence is a spatially and temporally random process. This makes it difficult for standard metrology methods to remove the errors induced by turbulence directly. However, since the process is random with zero net mean, measurement error can be reduced by averaging, with the error magnitude dropping by the square root of the number of averages.

Vibrations, on the other hand, have different characteristics. Sonic or seismic vibrations move the reference or test surfaces unpredictably, often at or near specific frequencies that depend on the origin of the driving forces. Depending on the difference between the measurement frequency and the vibration frequency, vibrationally induced measurement errors may not be random and so can be difficult to reduce with averaging alone. A range of solutions to this problem are provided below.

2. PHASE SHIFTING INTERFEROMETRY

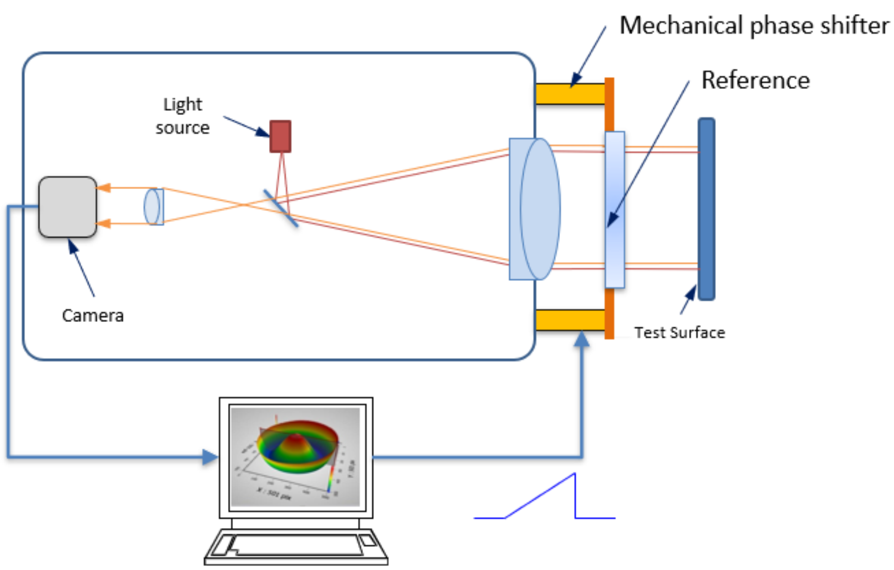

Figure 2: Fizeau Interferometer schematic

Phase Shifting Interferometry (PSI), has been the gold standard in interferometry for over 30 years [1,2]. It is reliable and trusted throughout the optics industry and is the most familiar method to interferometer users. “Measure using PSI” is frequently called out in standard operating procedures in optics labs and factories around the world. In a process similar to heterodyne detection developed for radio, PSI shifts the optical path difference between the two interfering wavefronts to produce interference at a known fixed frequency. The interference is detected and analyzed at the expected frequency using a Fourier filter produced from a fixed number of numerically weighted interferograms (a PSI algorithm) and the phase extracted modulo 2π at every interferogram spatial location [2]. The resulting phase map represents the difference between the two interfering wavefronts. With progress in electronic cameras and computer control in the 1980s, PSI became the most successful method for optical surface metrology and is still in widespread use today.

Since its inception, scores of PSI algorithms using different numbers of interferograms and phase shifts to address different error sensitivities have been proposed. However, the success of PSI can also be attributed to the Fizeau optical configuration generally used in a PSI measurement (Figure 2). The Fizeau configuration is optically simple, economical, and nominally common path, reducing instrument cost while improving performance [3]. When used with a common path geometry, PSI can measure wavefronts/surfaces with the highest possible lateral resolution and physical departure with the lowest level of optical aberrations and other errors compared to competing methods.

The chief disadvantage of PSI is its sensitivity to environmental disturbances. Acquiring multiple phase-shifted interferograms takes time, allowing environmental changes to influence the result by disturbing the phase shift rate. The vibrational error sensitivity of PSI algorithms is well understood and depends on the frequency and amplitude of the vibrational disturbance relative to the interferogram sampling rate. For small amplitudes, the sensitivity spectrum is described by the phase error transfer function [4]. Spatially, these errors often manifest themselves as a surface/wavefront distortion, called ripple, at twice the spatial fringe frequency, as illustrated in Figure 3 for a classical PSI measurement. For this reason, PSI measurements are traditionally performed in a dedicated environment isolated from vibrations and turbulence as much as possible. This requirement has made PSI difficult to incorporate in manufacturing settings.

Metrology testing generally involves passing a particular specification, for example, a Peak-Valley specification on a measured surface [5]. Environmentally induced ripple in a phase map can make an otherwise passing part fail the specification, creating waste and inefficiency. Metrologists with no choice but to use PSI in less than ideal environments often resort to repeated measurements to “sample” the environment, hoping that at least one of the measurements occur in a brief period of good conditions. This is a pragmatic solution but is time-consuming and does not inspire confidence in the measurement. Taking multiple averages is another common technique for mitigating environmental effects with PSI. However, while averaging can help reduce random errors, some sources of error, like vibrations, may not be fully random.

Classical PSI serves a wide range of critical quality control applications. With a suitable environment, it is a quick and repeatable way to characterize a wavefront with high accuracy. R&D applications where the goal is to develop and improve either a single part or a small batch usually have a dedicated metrology area with well-controlled environments. Small optics are easy to bring to an interferometer and can be measured with a short cavity so the whole setup, including the interferometer, easily fits on a table. Vertical workstation and test stand setups designed for fast spherical/aspherical optics frequently have vibration isolation built in, making PSI the fastest way to measure a surface or wavefront.

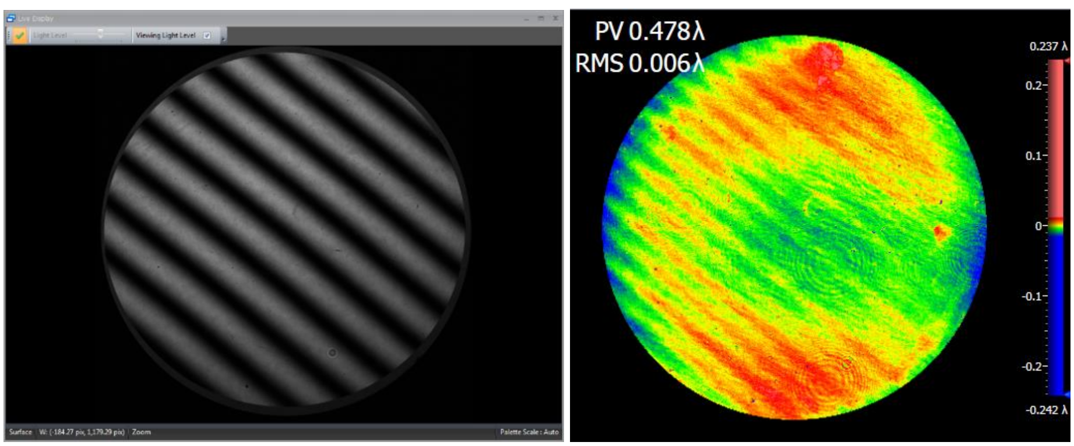

Figure 3: (Left) Fringe pattern on Live Display (Right) Fringe print through on data at double frequency

3. MODEL-BASED PSI

Overcoming sensitivity to vibration is the key to expanding the use of interferometers for optical testing in production and uncontrolled environments. A class of vibrationally-robust methods, called model-based PSI, is an effective way to make measurements in the standard Fizeau interferometer geometry with significantly improved performance [6]. Vibration-robust methods make PSI less vibration-sensitive without fundamentally changing the phase-shifting interferometry principles; all the positive features of PSI mentioned above are retained and part setup remains identical.

In a model-based approach, instead of extracting the interferometric phase via a fixed-frequency Fourier analysis, the interferograms are fit to a mathematical description of the interference using iterative nonlinear regression techniques.

Cavity surfaces are treated as rigid bodies and the model includes all the terms needed to account for vibrationally induced rigid body motion. Using a mathematical model conveniently allows terms describing other physical effects to be introduced as needed. For example, terms accounting for field-dependent phase shifts when applying mechanical phase shifting to fast spherical cavities is described in the above reference. Other advantages include: Nyquist limited resolution and departure, standard square-root noise reduction with averaging, quantitative measurements of the environment, useful measurement quality metrics, and lower phase noise compared to standard PSI due to the additional physical constraints and absence of a Fourier filter. The slow convergence of regression techniques is handled with innovations that include separately regressing conjugate variables so that the user experiences no significant delay between the data acquisition and the measurement results. To limit vibrationally induced contrast loss, all interferograms are acquired with a shuttered camera.

The most significant limitation of model-based PSI is a requirement for an initial wavefront (or surface) estimate to seed the iteration. This is often (but not necessarily) provided by analyzing the measurement with standard PSI. The initial estimate need not be very good, but the closer to the correct shape, the faster the convergence. The method used for the initial estimate defines the residual vibration sensitivity of model-based PSI. If a PSI algorithm is used, then the environmental limits are defined by where the PSI measurement fails catastrophically – i.e. when the algorithm introduces phase discontinuities, often called 2π errors [7]. This point can be estimated using the phase error transfer function, with knowledge of the cavity type (plano or spherical) and the environment vibrational spectrum. Vibration resistance is improved typically by 10× or more over standard PSI. Furthermore, with the rigid body motion handled; residual error is generally stochastic, so averaging provides the expected error reduction dependence proportional to the square-root of the number of averages. While model-based PSI reduces the need for vibration isolation, adding isolation can be used to increases the vibration tolerance.

A common way to quantify vibration tolerance is using Vibration Criterion (VC) curves, generally used to describe vibration levels in buildings and other structures. Figure 4 shows the approximate vibration limits, expressed as VC curves, for single frequency, piston-only vibrations when using QPSI, Zygo Corporation's commercial name for model-based PSI. QPSI vibration limits are VC-A when used with typical vibration isolation equipment (like an air table) and VC-D without. This is a significant improvement over PSI, whose limits are VC-F and VC-H with and without an air table, respectively.

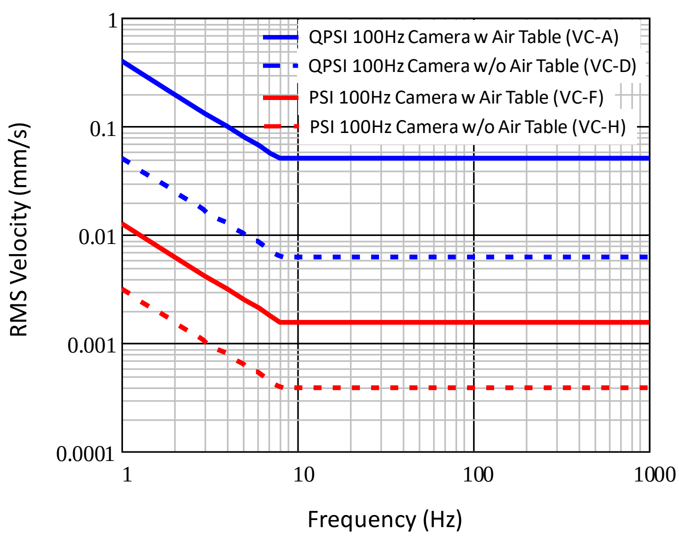

Figure 4: VC chart tracking PSI and QPSI performance

Model-based PSI is an attractive alternative to standard PSI for almost all applications and particularly when the highest performance is required but the environment is not ideal. As Figure 4 shows, QPSI can be used with an air table in environments as bad as VC-A. Frequently, production floors, even those with noisy equipment, fit within these limitations making QPSI a viable solution. This works well for inspection of production parts, both final and in process as there is no change to the standard operating procedure compared to PSI and throughput is increased by not removing the parts from the production floor. It also performs well for small labs or consulting businesses where having a large air table is not practical. If the surrounding environment is stable to better than VC-D, the interferometer can acquire reliably while on the floor or a standard conference table. Downward looking interferometer setups where the part and reference are coupled also benefit from model-based PSI as most motion is rigid body. Generally, any application where ripple is seen frequently during PSI-measurement can benefit from model-based PSI.

4. SINGLE FRAME MEASUREMENTS

Environments too extreme for environmentally robust methods necessitate environmentally insensitive, or "dynamic", methods. It is noteworthy that historically, the earliest interferogram analysis methods were the environmentally insensitive type. Cavity tilt fringes were introduced by interfering a surface reflected wavefront with a tilted reference wavefront, producing an interferogram with line fringes. These fringes "carry" information about the reflective surface through fringe deviation from linearity. A single picture of the interferogram was taken, developed, and painstakingly analyzed by hand to determine the "fringe straightness", from which it is possible to measure the departure from the reference wavefront [8]. Practical considerations meant the fringe density was relatively low, allowing only estimates of low order surface form deviations.

The advent of computers, electronic cameras and a Fourier analysis first described by Takeda [9], eliminates the manual labor of fringe analysis and improves performance, with the result that this spatial phase shifting method is a well-established surface measurement technique often used in extreme environments. Environmental fluctuations are effectively frozen by using a single short exposure interferogram. Modern cameras can easily produce exposures in the 10s of microseconds range. The method's analysis steps are shown in the figure below. First, a Fourier Transform is applied to a single interferogram containing dense carrier fringes to produce a spatial spectrum. Then, the 1st order carrier fringe frequency is identified and isolated with a filter and the filtered spectrum is inverse transformed. The surface topography is encoded in the phase of the complex inverse transform map.

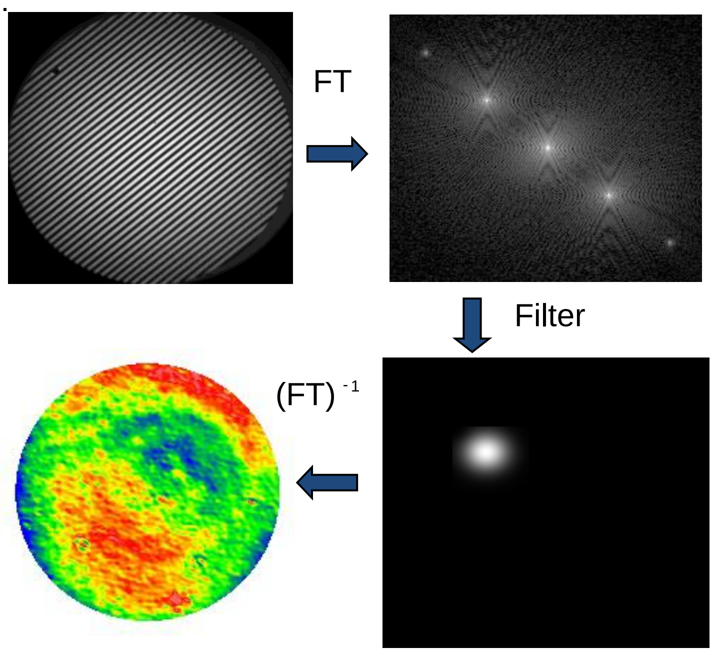

Figure 5: Carrier fringe method for spatial phase shifting: A Fourier transform reveals the frequency content of the interferogram. Software identifies the frequency corresponding to the carrier fringes, isolates this information, then inversely transforms the filtered Fourier information to obtain a complex-valued image. The phases in the complex image correspond to the surface heights.

An alternative to spatial encoding with tilt fringes is to use polarization. Polarization-based dynamic measurements employ orthogonally polarized test/reference beams and use birefringent elements to simultaneously acquire multiple, synchronous, phase-shifted interferograms [10,11]. The wavefront/surface is then evaluated from those interferograms. Though spatially encoded systems are more common than polarization-based systems, both have similar performance.

The main differences involve the calibration techniques for removing residual error, because the origin of those errors is different between the two [12].

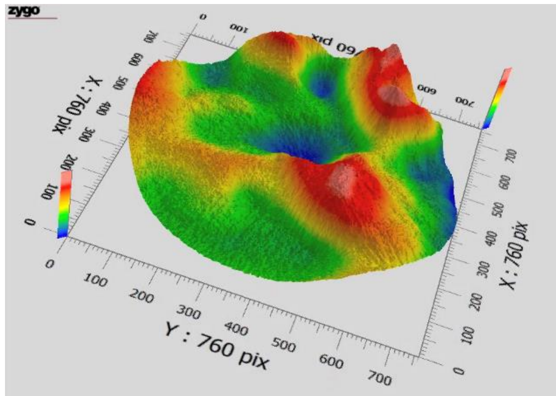

Figure 6: Video illustrating real-time averaging to reduce the effects of turbulence in a poor environment. DynaPhase Averaging.wmv http://dx.doi.org/10.1117/12.2569458.1

Though a significant advantage of single-frame interferometry is insensitivity to environmental fluctuations, the fact that a surface or wavefront can be determined with a single frame enables additional benefits. For example, the method performs effective, high-speed "smart averaging"—a continuous average in real-time, allowing the user to visually decide when sufficient averages have been taken (Figure 6). The method also lends itself well to large aperture (12" and larger) systems because no mechanical phase shifting is required; it can be difficult to precisely shift a large optic which can weigh hundreds of pounds. Since measurements can be taken in a single frame, it is possible to present a "live" height map updating in real-time with live Zernike feedback or capture upwards of 1000 frames at rates of 50 or more frames per a second and process afterwards to capture change over time in data and/or movies.

By analyzing each interferogram individually, one can enable dynamic measurements in applications such as deformable mirrors or adaptive optics where the sample shape is intentionally changing over time. It is ideal for setting up large telescope mirrors where environmentally well-controlled cavities are impossible, and is also useful for smaller telescopes, and real-time alignment of optical assemblies. When needed, the acquired interferograms can be synchronized with an external trigger to enable the measurement of transient events. Dynamic methods have even been used to track airflow in extreme environments like wind tunnels.

Single-frame interferometry is not without its drawbacks. The Fourier filter must not only isolate the positive 1st order spectral peak, but it must also suppress everything else, including DC and the 2nd order spectral peak. Any leakage from DC or the other peaks produce regular surface/wavefront distortions similar to ripple in PSI. This requirement means that the highest measurable spatial frequency is less than half of Nyquist, reducing the spatial resolution. A related filtering effect is the reduction of the measurable test surface/wavefront departure by the same factor [13]. The analysis must be sophisticated enough to handle a distortion referred to as "Gibbs ringing", a ripple-like effect which occurs anywhere fringe discontinuities are present, often observed at the test part edges. There are well-documented analysis approaches to address this phenomenon, but they tend to be computationally intensive, reducing measurement throughput.

The method has two additional drawbacks, each of which can be mitigated with well-designed, high-quality optical systems. The first drawback is optical aberration introduced by propagating a tilted wavefront through the instrument optical system [13]. Generally, these aberrations are low order and can be satisfactorily reduced with a combination of system and in-situ calibrations. For best results, measurements and system calibrations must be performed with the same reference tilt. Software guides the user to precisely set the reference tilt to a known, fixed value. This fixed reference tilt means that one-time factory calibrations can compensate for some baseline low order distortions and power. Optional additional in-situ calibrations account for low-order spatially odd aberrations, like coma and astigmatism. These odd-order aberrations are handled by averaging measurements with opposite tilts since the odd-order aberrations then cancel [14]. High-quality optical system design and fabrication reduce the magnitude of residual retrace errors.

Even with these drawbacks, the Carrier Fringe method is a well-established and widely used surface profiling technique when environmental stability is too poor for other methods.

5. SELECTING A MEASUREMENT MODE

Metrological needs frequently change from part to part and application to application. Choosing the measurement method is an important element of part set up. The first step is determining how well controlled the cavity and environment are. If the environment has been measured for vibration criterion, the VC curves (Figure 4) can be used as a guide to select a measurement mode. If not, looking at the fringe motion of an aligned cavity's interferogram is a way to judge the stability of the cavity. Stable cavities and/or setups on vibration isolation tables will have static fringes and can use any of the discussed methods so PSI or model-based PSI are recommended because vibration may be less of a concern and the on-axis methods will maximize resolution while minimizing retrace and aberration error. As movement shown in the live interferogram increases, model-based PSI, or even carrier fringe mode may be required, depending on the severity of the motion.

The next step is evaluation of error sources, which include vibration or air turbulence, rigid-body or complex motion, and systematic or random motions. Air turbulence, where the optical path is being changed by random air currents, can be counteracted with averaging while vibration, which causes the part to physically move relative to the reference, requires a measurement method change. Rigid-body motion of a surface can be compensated for by model-based PSI, but if the motion causes physical part deformation then dynamic measurements will be required. Large amounts of both systematic and random vibration are best addressed using carrier fringe measurement, but for random vibration it is important to average to reduce the random form error frozen in each dynamic frame.

A final consideration is the application requirements. If maximum lateral resolution is needed, then an on-axis measurement mode must be selected. If instead real-time feedback is needed, then a dynamic mode is the best solution. Evaluating these needs before making a measurement will increase confidence in the metrology. A successful strategy for a new application is simply to test if a given measurement mode provides acceptable results, starting with the highest accuracy and moving to the greatest resistance to vibration, moving from PSI to model-based PSI, then to dynamic methods. For this reason, it is beneficial to have an instrument with all three categories of measurement methods to best optimize each part setup, especially if metrology is needed for a range of applications.

6. CONCLUSION

Commercial interferometers have a range of measurement modes to satisfy metrology needs for the full range of environments and applications of the optics industry. Each of the three categories: phase-shifting, vibration robust methods such as model-based PSI, and single-frame or dynamic measurements such as the carrier fringe method, have their advantages and drawbacks. PSI is highly trusted in the optics community and provides reliable results in well-controlled environments, but it is very susceptible to vibration. Model-based PSI improves vibration performance without compromising measurement quality. Carrier Fringe methods can acquire data in virtually any environment but introduces errors due to the off-axis optical path compared to the other two on-axis measurement modes. It also reduces the lateral resolution of the interferometer. These feature sets correspond well to different applications, and user guides are available on how to choose the optimal measurement method [13].

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