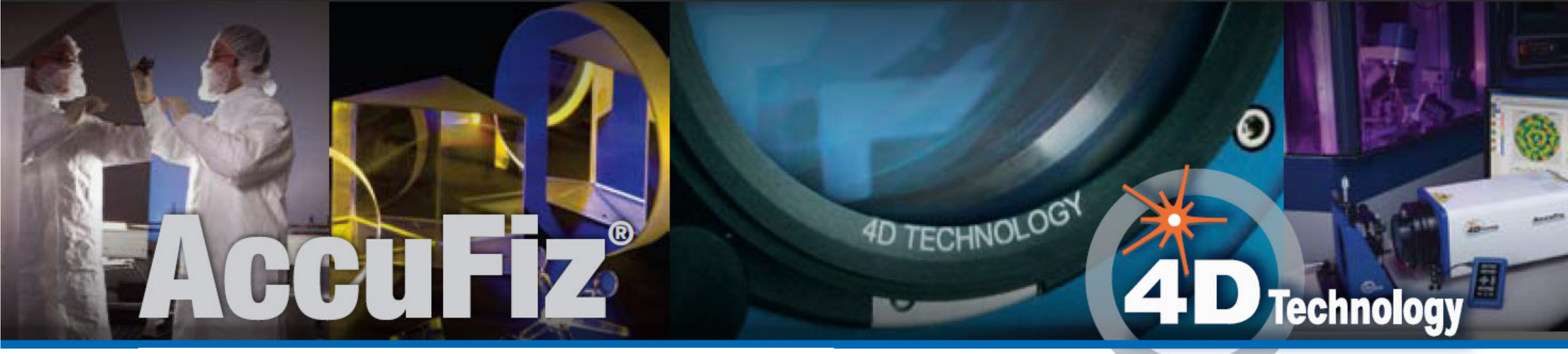

Fizeau Interferometer Fact Sheet

This document provides detailed information to frequently asked questions about the AccuFiz® family of compact laser interferometers. This FAQ will address the following aspects of the AccuFiz product line:

- AccuFiz family (models and options)
- Dual measurement modes
- Accuracy and calibration
- Resolution, ITF and zoom
- Repeatability and precision
- Adjustable source size
- Pixel count and instrument performance
- Slope capabilities and aspheric measurements.

AccuFiz Family

The AccuFiz family includes wavelengths from visible (632.8nm) through IR (10.6µm). Apertures of 100mm (4”) and 150mm (6”) are available. Beam expanders are available to convert the 4” aperture to 6, 12 and 24”. Unstabilized and stabilized sources are offered. Stabilized sources provide higher power and a longer coherence length which does not drift with temperature, simplifying long-cavity measurements. Table 1 shows the available AccuFiz models.

Table 1. AccuFiz Product Line

AccuFiz Model	Stabilized Laser	Wavelength	Camera	Extended Source	Optical Zoom
B100, B150	No	633 nm	512 x 512, 12-bit	No	No
E100, E150	No	633 nm	1.44 MP, 12-bit	Yes	Optional 6X
E100S, E150S	Yes	633 nm	1.44 MP, 12-bit	Yes	Optional 6X
H100S, H150S	Yes	633 nm	6 MP, 12-bit	Yes	No
E100-532, E150-532	Yes	532 nm	1.44 MP, 12-bit	Yes	Optional 6X
S100-1053, S150-1053	Yes	1053 nm	1.44 MP, 12-bit	Yes	Optional 6X
SWIR	Yes	1550 nm	512 x 512, 12-bit	Yes	No
MWIR	Yes	3.39 or 3.8 µm	480 x 480, 12-bit	Yes	Yes, 2X
LWIR	Yes	10.6 µm	512 x 512, 12-bit	Yes	Yes, 2X
All models available with 100 mm (4”) or 150 mm (6”) aperture.					

Dual Measurement Modes

The AccuFiz operates in both temporal phase-shifting interferometry (TPSI) mode and in optional Dynamic Interferometry® mode which captures data with a single camera frame. Dynamic mode can effectively freeze out vibration and permits operation in a wide variety of environmental conditions, including testing with remote cavities and large beam expanders.

In standard TPSI mode (**Figure 1**) several intensity frames (typically 5 to 13) are captured sequentially with a precisely-controlled phase-shift between each (typically 60 or 90 degrees). This shift corresponds to a fraction of a wavelength of motion of the reference optic with respect to the test path.

Under ideal, low vibration conditions, TPSI produces very high spatial resolution measurements with an uncalibrated accuracy limited only by the reference optics. However, vibration or air turbulence can introduce systematic measurement errors, and if motion is induced on the order of $\lambda/4$ between frames errors may be generated that are so large that the wavefront cannot be reconstructed (unwrapping failure).

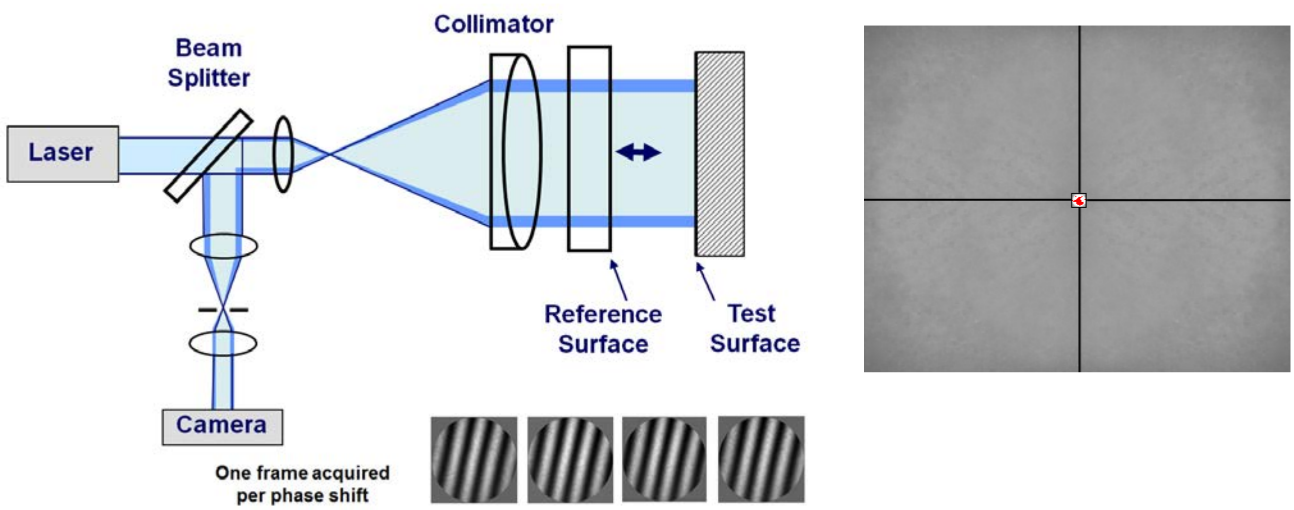

Figure 1. Schematic diagram of four-frame temporal-phase shifting. The alignment screen at right shows that both the test and reference beams are on-axis and passing through the center of the alignment reticle.

The optional Dynamic mode acquires data in a single camera frame, which reduces the stability requirements for the test setup and cuts acquisition time from 100's of milliseconds to a fraction of a millisecond. **Dynamic mode affords a 2- to 3-order of magnitude increase in robustness, making it the recommended mode for noisy environments.**

Dynamic mode utilizes a "spatial carrier" optical arrangement that produces a linear phase-shift across the pixels. This is accomplished by slightly tilting the reference beam to impart a small angle between the reference and test beams (typically 0.15 degrees). **Figure 2** illustrates the basic arrangement and the resulting spatial phase-shift that occurs across a region of 3x3 pixels.

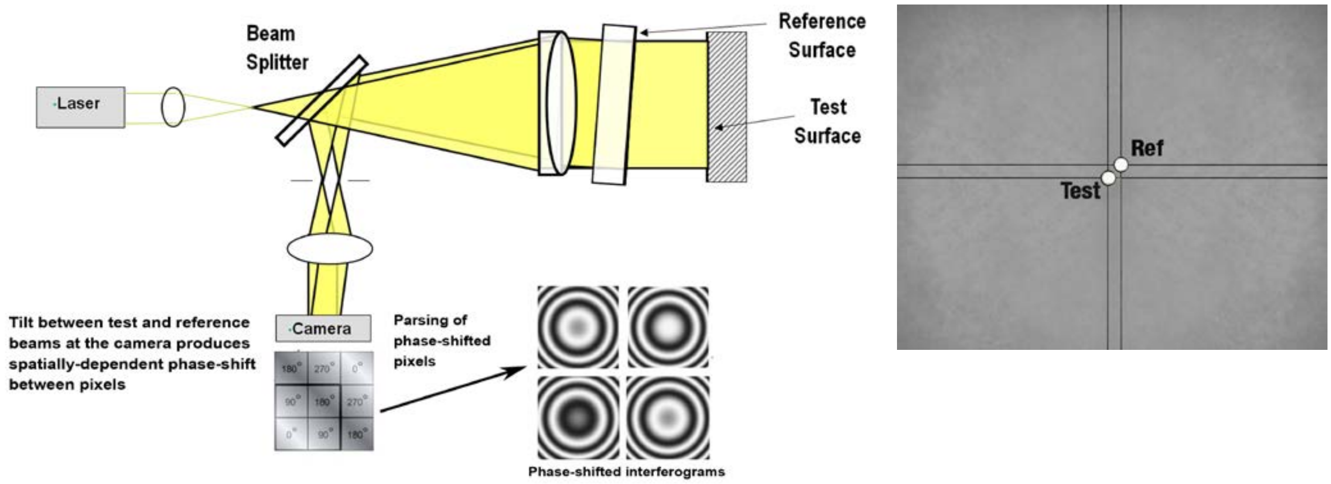

Figure 2. Schematic diagram of spatial-phase shifting Dynamic mode. The alignment screen at right shows the test beam on-axis and passing through the center of the alignment reticle, while the reference beam is aligned slightly off-axis.

The resulting pattern can be analyzed in several ways to calculate the wavefront difference between the reference and test optic. The AccuFiz uses a proprietary, convolution-based approach that has the advantage of producing a phase-map with the same number of pixels as the detector. Data is acquired on a single shot basis, affording excellent vibration immunity, and can be averaged to obtain measurement precision better than the single-frame shot-noise floor limitation, just as in TPSI measurements. Dynamic mode also enables the AccuFiz to measure with large beam expanders or remotely located reference optics that do not have temporal phase-shift capability.

Advantages of each mode. Temporal phase-shifting provides excellent resolution in well-controlled environments. Dynamic mode permits operation in a wider variety of environmental conditions (**Figure 3**), over long path lengths, with large optics, in turbulent rooms and in situations where vibration isolation is not practical.

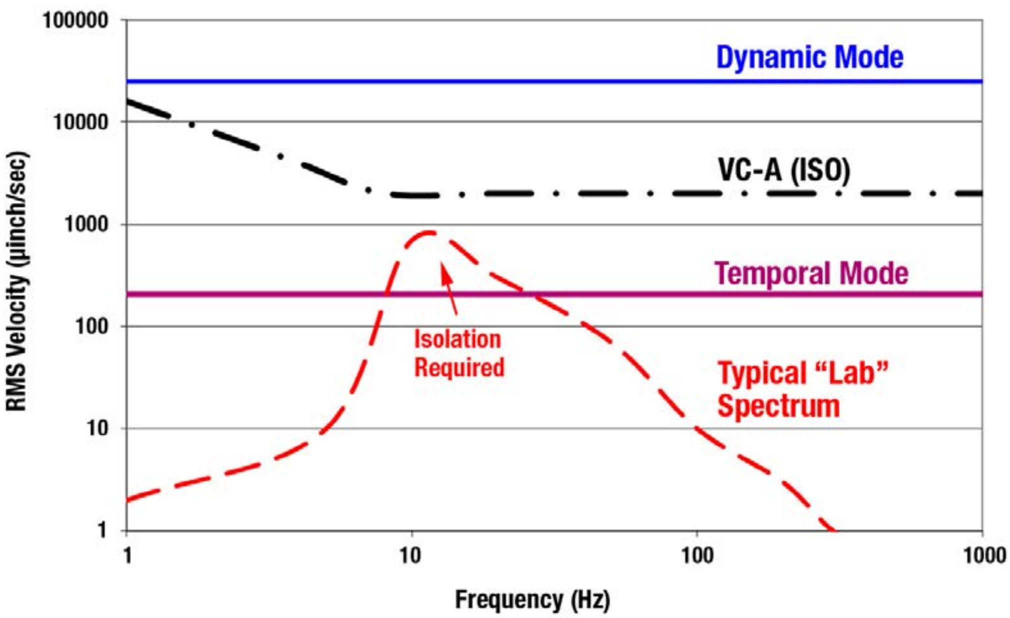

Figure 3. AccuFiz response to vibration. Dynamic mode functions in virtually any environment, whereas temporal mode requires isolation even in typical lab settings.

High Accuracy

***Uncalibrated Accuracy**.* In standard TPSI mode, the reference and test beam travel on essentially identical paths though the imaging system of the interferometer. This arrangement makes the system largely insensitive to the quality of the imaging optics. Thus the limiting factor in calibration is the quality of the reference surface itself.

In Dynamic mode the reference and test beams travel on slightly different paths through the interferometer. Thus, the uncalibrated accuracy is affected by the quality of the interferometer imaging system and, specifically, the off-axis aberrations introduced in the system. The optical system in the AccuFiz was designed to mitigate this off-axis aberration.

***Calibrated Accuracy**.*

Calibration is used to achieve high accuracy in dynamic mode. Several calibration methods are available:

1. **Reference Subtraction**. by subtracting a reference (i.e., a “calibration artifact”) from each measurement. This is accomplished by taking an averaged measurement (typically 16 or more individual measurements) of a very high quality surface. The resulting averaged measurement is then saved as an “optical reference” in the 4Sight interface and will automatically be subtracted from subsequent measurements.
2. **4-point technique**. When a calibration artifact is unavailable or prohibitively expensive, a proprietary technique using a sequence of measurements can be employed to calibrate the measurement.

A calibrated measurement will give results with accuracy essentially as good as the reference surface; for example, if a λ/20 flat is used as the calibration artifact then the AccuFiz will achieve up to λ/20 performance in dynamic mode.

Absolute sphere and flat measurements are also included in 4Sight software for high-accuracy measurements.

High Resolution at All Zoom Settings

AccuFiz interferometers have a high-performance optical imaging system that is matched to the full array resolution and affords very low retrace error and low spurious reflections. The detector-limited optical design, coupled with high resolution sensors, gives the AccuFiz far superior resolution, even at 1X zoom, than standard systems with built-in optical zoom.

Continuous optical zoom in most interferometers comprises many optical elements, which can lead to both high retrace error and to spurious reflections from the many optical surfaces. Moreover, the use of commercial optical zooms in many interferometers does not result in improved spatial resolution (see ITF discussion below).

Because of these limitations optical zoom often offers little or no benefit for imaging resolution and can, in fact, be detrimental.

The AccuFiz SmartZoom™ system allows the same high resolution at *all* zoom settings, provides fast zoom and pan functions and eliminates the need to laterally calibrate for each zoom change.

The fundamental parameter to understand when evaluating an interferometer’s imaging resolution is not the quoted "zoom" factor or even the detector pixel count, but rather the instrument transfer function (ITF). The ITF corresponds to the reported height of a surface of a given spatial period compared to the actual height. **Figure 4** illustrates how the measured and actual height of a surface degrades as the spatial period decreases. All interferometers are limited at higher spatial frequencies by either their optical imaging system or the detector resolution.

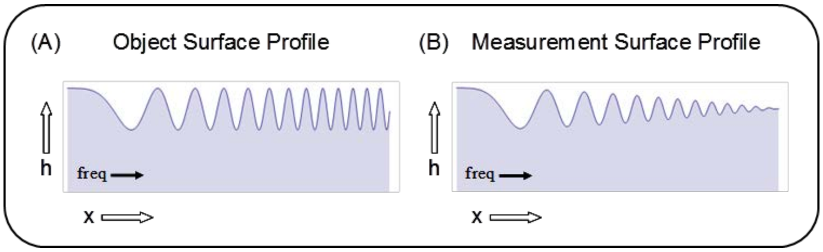

Figure 4. Fall-off in measured verses actual surface height as a function of increasing spatial frequency (decreasing spatial period).

An interferometer's ITF can be represented by plotting the instrument response as a function of spatial frequency. An ideal response would be flat across the entire frequency band; however, the finite size of the detector pixels will cause a reduction of signal at higher frequencies. **Figure 5** shows the theoretical ITF curves for various AccuFiz models.

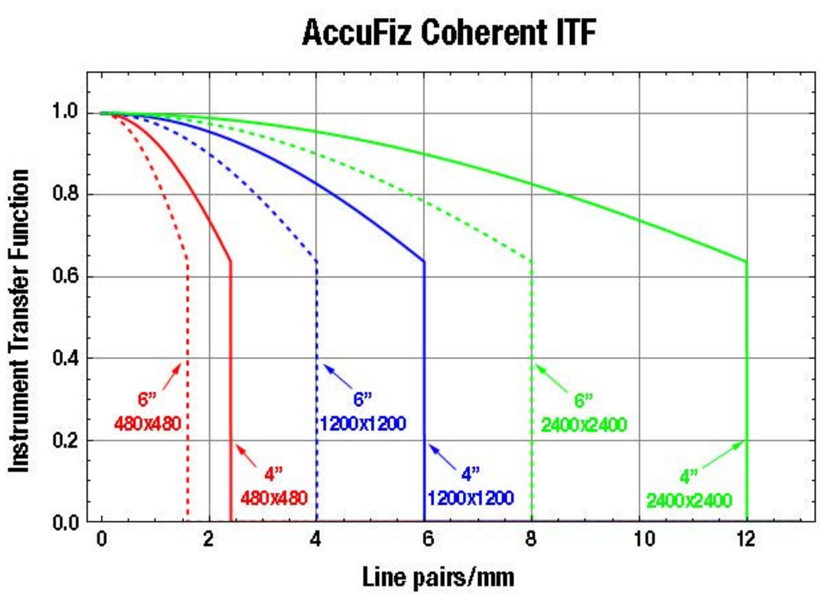

Figure 5. Instrument Transfer Function (ITF) for various AccuFiz models. The ITF is equivalent to the normalized instrument response as a function of spatial frequency (decreasing spatial period).

In **Figure 6** the detector-limited response for a 100mm aperture, 1.44MP AccuFiz is shown as a dotted blue line. The blue trace represents the actual, measured ITF with the test grating structures positioned vertically, while the red trace shows the results with the grating positioned horizontally. This figure, therefore, demonstrates the detector-limited performance of the AccuFiz.

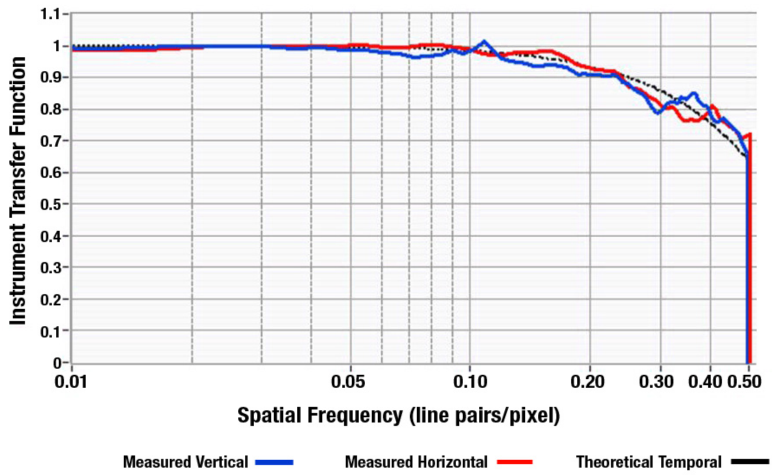

Figure 6. Measured ITF for a production 100mm aperture, 1.44MP AccuFiz. Dotted line is the theoretical maximum (detector-limited response).

Other interferometers' imaging systems do not achieve detector limited performance even at 1X magnification. For these systems, zooming the image merely increases the imaging spot diameter at the same rate as the pupil magnification; in other words, even though the pupil image is getting bigger on the display, the ITF is not changing and there is no actual improvement in lateral resolution. The blurred image is simply oversampled and provides no additional information content.

Figure 7 shows the ITF for an AccuFiz with 1.44 MP sensor compared to other interferometers at various zoom settings. Here, the ITF is measured with respect to lateral spatial coordinates; that is, the ITF is plotted in physical units (line pairs per millimeter), which enables us to evaluate the value (or ineffectiveness) of zoom magnification. **The AccuFiz has a better ITF response at 1X zoom than competitive Models A and B, even at 3X and 4X zoom, respectively**.

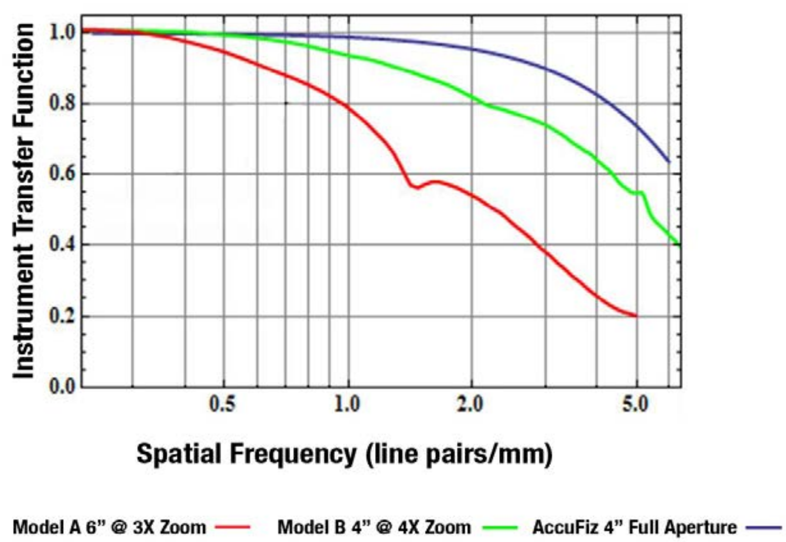

Figure 7. Comparison of a 4" aperture AccuFiz at full aperture vs other models of interferometers while zoomed.

Spatial Resolution. The spatial phase-shifting approach and Dynamic mode processing algorithm have been designed to ensure that high spatial frequency information is retained.

Figure 8 shows the Dynamic mode response (green) compared to a standard TPSI measurement made with a detector of 1200 x 1200 pixel count (red) and that of a TPSI measurement made with a VGA resolution detector (blue). Note that even the high resolution TPSI measurement has some attenuation of high frequencies due to the finite pixel size of the detector. While the Dynamic mode processing method has some additional attenuation around 1 line pair/mm compared to a VGA resolution detector, the Dynamic mode response extends to considerably higher frequencies, approaching that of the full detector array, which allows it to capture high slope measurements. The resulting resolution is approximately 70% of the maximum possible in TPSI mode. Therefore, in Dynamic mode a detector with 1200 x 1200 pixels has a response out to a frequency that is equal to the cutoff frequency for a detector of 840 x 840 pixels.

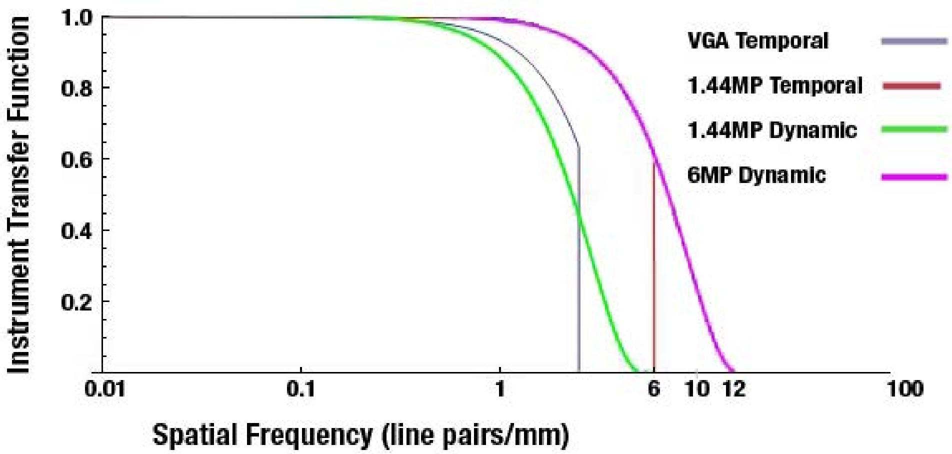

Figure 8. Frequency response (at the aperture) of AccuFiz in standard temporal phase-shifting (red), Dynamic mode (green), and with a VGA resolution detector (gray) as a function of spatial frequency (line pairs/mm). Dynamic mode has extended frequency response beyond VGA, increasing its slope capture range.

Repeatability and Precision

During factory qualification 4D measures two parameters: RMS Repeatability and RMS Precision.

Repeatability and Precision both quantify the level of random error present in the measurement for a given number of averages (M). Random error may be due to electrical noise, optical shot noise, or environmental factors such as air turbulence.

Repeatability is most relevant when considering only the overall wavefront/surface quality (e.g., how well an optical system is aligned), while Precision is more relevant in evaluating the level of random error at each point in the spatial distribution of the wavefront/surface shape (e.g., when using deterministic computer controlled polishing).

To determine Repeatability and Precision we first define these terms:

M - The number of single measurements in an averaged measurement

N – The total number of Averaged measurements. This is the sample size for statistical calculations

$\boldsymbol{S(x,y)}$ - single surface map measurement

$\boldsymbol{A_n(x,y)}$ - Averaged surface map, $A_n(x,y) = \frac{1}{M}\sum_{m=1}^{M} S_m(x,y)$

$\boldsymbol{SA(x,y)}$ – Super Average map, $SA(x,y) = \frac{1}{N}\sum_{n=1}^{N} A_n(x,y)$

$\Delta_n(x,y)$ – Difference surface map, $\Delta_n(x,y) = A_n(x,y) - SA(x,y)$

σ_{An} – RMS value of an averaged surface map, $\sigma_{An}^2 = \frac{1}{\sum x \sum y} \sum_{x,y} (A_n(x,y) - \overline{A_n})^2$

$\sigma_{\Delta n}$ – RMS value of a Difference surface map, $\sigma_{\Delta n}^2 = \frac{1}{\sum x \sum y} \sum_{x,y} (\Delta_n(x,y) - \overline{\Delta_n})^2$

Precision and Repeatability are calculated according to:

RMS Repeatability ≡ standard deviation of RMS value of averaged surface maps,

$$\sigma_{RMS}^2 = \frac{1}{N-1} \sum_{n=1}^{N} (\sigma_{An} - \overline{\sigma_{An}})^2$$

RMS Precision ≡ Mean standard deviation of Difference Surface maps,

$$RMS\ Precison = (\overline{\sigma_{\Delta n}}).$$

For standard repeatability and precision measurements 4D uses M = 16 and N = 10. AccuFiz repeatability and precision are summarized in **Table 2**.

Table 2. Temporal and Dynamic mode Repeatability and Precision

	Temporal (9 frame)		Dynamic Mode	
	RMS Repeatability (wv)	RMS Precision (wv)	RMS Repeatability (wv)	RMS Precision (wv)
AccuFiz Point Source	0.0002	0.001	0.001	0.002
AccuFiz Extended Source	0.00008	0.0005		

Specifications apply to 4-inch AccuFiz systems with 1.44MP and 6MP sensors. Factors influencing performance are discussed in the following sections.

Adjustable Source Size Suppresses Artifacts

The AccuFiz allows you to adjust the diameter of the light source to minimize measurement artifacts such as diffraction rings while maintaining adequate fringe contrast (**Figure 9**).

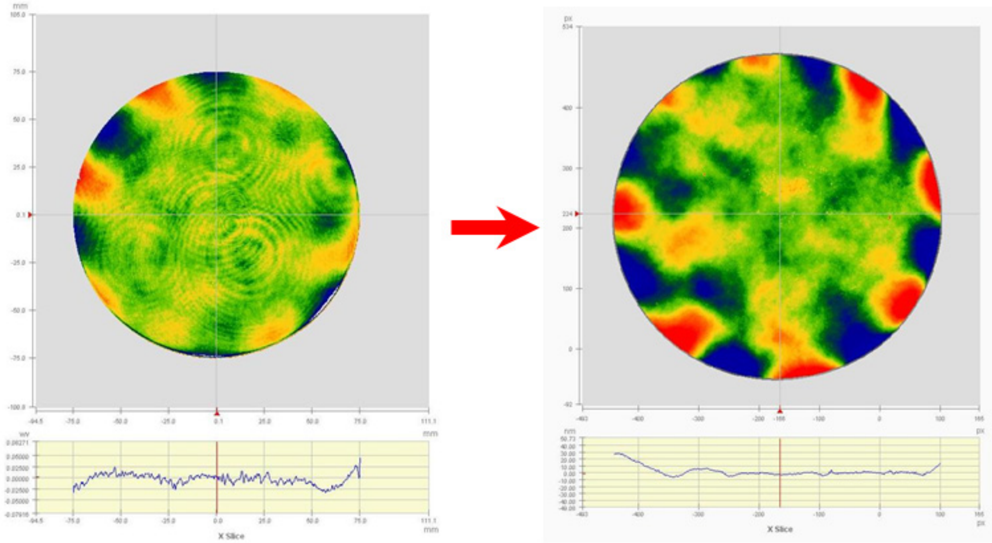

Figure 9. Typical artifact suppression due to dust on an optic.

A typical interferometer offers only point source illumination while the AccuFiz allows the source size to be adjusted continuously between point source and approximately 2mm. In general, a large source size will minimize measurement artifacts such as diffraction rings which may be caused by imperfections in the optical system (dust, pits) or stray reflections from optical surfaces. However, a larger source size will also reduce fringe contrast for large cavities. Therefore, any given test setup has an optimum source size to minimize artifacts while preserving the fringe contrast for a given cavity size.

Note: Because dynamic mode is typically used for measurements in which there is a long cavity (i.e., the test part is located far from the instrument) it is recommended that a point source be used in dynamic mode. For this reason, **Table 2** does not list performance with extended source and dynamic mode. In practice, however, it is possible to use some degree of extended source with shorter cavities in dynamic mode.

When measuring corner cubes and prisms in single pass the source diameter must be minimized to a point source.

The source size is easily adjusted using the **Smaller** and **Larger** buttons on the hand controller (**Figure 10**). Try to maximize the contrast of the primary fringes while minimizing spurious fringes around surface defects or contaminants (**Figure 9**). The indicator in the center of the **Source** button shows where the source diameter is currently set relative to its total range of travel.

To allow for operation over a wide variety of environmental conditions, the source size can be adjust *through* point source; that is, the actual "point source" position is slightly to the right of the minimum setting on the hand controller.

Figure 10. Remote controls for adjusting source diameter, focus, zoom and pan, and for taking a measurement, are available on-screen, on a dedicated remote, and through mobile devices.

Pixel Count and Dynamic Performance

The pixel count and size for each detector are summarized in **Table 3**. The table shows the trade-off between resolution and acquisition speed (and thus vibration insensitivity).

Table 3. Pixel Count and Integration Time

	Number of Pixels	Typical Integration Time*	
	(H x V)	12 bits	10 bits
AccuFiz E (1.44 MP)	1200 x 1200	1 ms	250 µs
AccuFiz H (6 MP)	2400 x 2400	4 ms	1 ms
AccuFiz H Binned Mode	1200 x 1200	1 ms	250 µs

* With uncoated transmission flat and reference flat, and stabilized laser.

Pixel Count

The typical fill factor for the full aperture (D/H = D/V) is 90% as shown in Figure 11 below. For a circular aperture the actual number of pixels in the map is reduced by $\frac{\pi}{4}(\mathbf{0.9})^{\mathbf{2}}$, or 0.64.

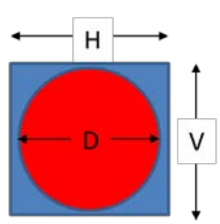

Figure 11. Fill factor definition.

Dynamic Performance

Temporal measurements require low vibration over a long period of time, typically 100s of milliseconds for multi-frame acquisition. Given such long frame rates, integration time is not a particular concern. However, for dynamic measurements the integration time is inversely proportional to the vibration immunity of the system.

The exposure time for a 1.44MP AccuFiz is only 1msec, which provides ~12 bits of data (with the stabilized HeNe option). This represents 1000Hz from the point of view of vibration (in dynamic mode). With this exposure the AccuFiz can tolerate a substantial amount of out-of-plane vibration (e.g., > λ/4 at 1000Hz), with only a small loss of contrast. In practice, this exposure time works well for almost any typical lab environment.

In cases in which there is a significant vibration issue, exposure values <500 µsec can be used (the camera is capable of 10 µsec). Using shorter exposures will reduce the data to less than 12 bits; however, additional averaging can be employed to obtain the same measurement noise floor. The need for this typically only arises in applications with significant forced mechanical vibration, as when looking into a vacuum chamber.

Because of the higher pixel count, the 6MP AccuFiz has an exposure time of 4ms, or 250Hz from the point of view of vibration. This is very robust for typical lab environments. The same conditions apply as above: exposure can be reduced but trade off a degree of bit depth in the process and an increase in required averaging. The 6 MP camera can be operated in a binned mode which makes it equivalent to a 1.44 MP system in terms of integration time.

Other System Options

The AccuFiz Surface Isolation Source (SIS) is an optional, external laser source that excludes all but the surface of interest of transparent, plane-parallel optics. With the SIS both surfaces of a transparent optic can be measured, and transmitted wavefront error, optical thickness and homogeneity can be calculated. The adjustable path match mechanism provides flexibility, letting you dial in any surfaces that are within 88 through 112 millimeters from the aperture.

4Front Fast Acquisition Software provides high-speed acquisition, measurement, analysis and display of wavefronts measured with the AccuFiz. 4Front can be used to measure and align optical systems in real time or to rapidly average large numbers of measurements. Data acquired in 4Front can be further post-processed in 4Sight.

4Front can also be used to generate a calibration reference measurement for the AccuFiz when a reference artifact is unavailable. The reference measurement can also be imported into 4Sight as a reference surface.

Switchable output polarization accounts for reflectivity and other issues to enable measurement of polarizing optics.

The **Adjustable Beam Ratio** option for dynamic mode lets you selectively adjust the output of the reference and test beams, allowing you to measure coated and uncoated optics without an external attenuator.

The **Motorized Tip/Tilt** mount provides remote operation of the reference optic tip and tilt. It can be attached to the front of the AccuFiz or can stand alone away from the instrument.

Beam Expanders convert a 4” aperture AccuFiz test beam to 6”, 12” and 24” diameters, making it possible to use a standard AccuFiz to cost-effectively measure large optics.

A **High power alignment laser** produces a bright, visible beam which makes it easy to align low return optics or systems.

Conclusion

The compact AccuFiz interferometer offers an unmatched combination of performance, quality and value, for high-accuracy surface shape and transmitted wavefront quality measurements of optical components and systems.

With dual measurement modes, a diffraction-limited imaging system, outstanding accuracy (particularly at mid-spatial frequency, and excellent precision, resolution and repeatability, the AccuFiz is the best choice for measuring small and large optics, optical systems, and precision surfaces.