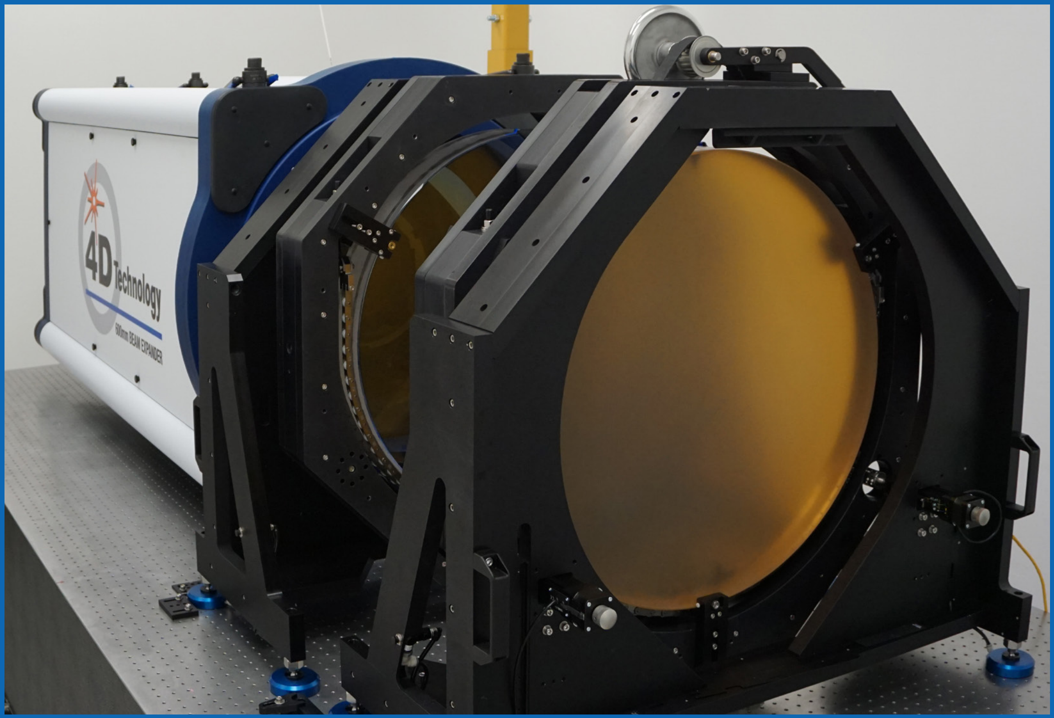

Considerations in designing very large aperture interferometers

A WHITE PAPER

4D Technology
A Nanometrics Business Unit

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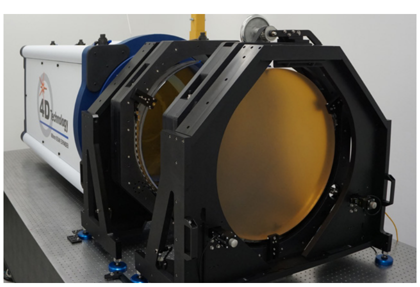
On the cover: 600mm Fizeau Beam Expander and Accessories

The 600mm AccuFiz Fizeau interferometer system from 4D Technology incorporates a number of improvements to performance, usability, and stability that are the result of a ground-up approach to large aperture system design.

It uses a 100mm AccuFiz as its data acquisition engine, and a cleverly designed beam expander system to provide high flexibility and ease of use in a package that delivers uncompromisingly high accuracy measurements.



Download the standard AccuFiz data sheet:

Click here for the AccuFiz interferometer **Data Sheet**

Scaling up Fizeau interferometers without undercutting performance and usability

Considerations in designing very large aperture interferometers

By Erik Novak, Ph.D.

Leaving History Behind

Laser Fizeau interferometers are the workhorses of optical testing. With proper configurations and accessories, these instruments enable characterization of flats, prisms, concave and convex lenses, and even aspheric elements. While many laser Fizeau systems produce output beams which are up to 6” in diameter, the increased production of telescopes, satellites, high-power lasers and other novel optical systems has been creating a greater need for large aperture systems— that is, Fizeau interferometers with an output aperture larger than 12” (300mm) in diameter.

Historically, large Fizeau systems have been designed using two different approaches. Some have been custom-built with unique, one-off housings and optical elements, while other systems have used smaller interferometers combined with off-axis, air-table-mounted optical beam expanders to achieve the necessary aperture size. Today, modern materials, design methods, and software engines can reduce complexity, improve precision and repeatability, and greatly enhance the usability of large-aperture laser Fizeaus. With them a variety of applications can be realized.

Critical design elements are needed for next-generation, large-aperture interferometers. Advances reduce environmental effects, speed acquisition times, improve robustness, and provide higher-quality data for end users.

Let’s consider a 600mm (24”) aperture system. Among the most challenging of instruments, a 24” system can utilize design principals that smaller systems can benefit from in the same way.

Mechanical Design Issues

The optical design of any measurement system is of course extremely important. However, even optics from the best possible design will fail to provide consistent, high-quality data if they may become misaligned or defocused. External factors like temperature changes, mechanical stress, or vibration can induce defocus or changes in alignment. An historical 24” system, such as those produced by Wyko Corporation to measure the optics for Lawrence Livermore’s National Ignition Facility (NIF), were custom-built. Each optic was hard-mounted to a large air table. While this produced unprecedented performance in the 1990’s, the design meant that the systems were not portable, they were susceptible to small misalignments due to multiple system folds, and they were difficult to service due to their many custom components.

Choose a diffraction-limited measurement engine

In 2017 4D Technology was given the opportunity to design and build the next generation large-aperture systems for measuring high-power laser optics and other tightly tolerance components. 4D took a ground-up approach to ensure the best possible performance, stability, and reliability. As the 4D 4” (100mm) aperture AccuFiz laser Fizeau already had diffraction-limited imaging, a very compact and lightweight design, and the highest instrument transfer function (ITF) of any commercial interferometer system, this was chosen as the fundamental measurement engine.

Combining this interferometer with a beam expander would ensure that most of the system was already qualified to a high degree of performance and easily supported into the future because it is a standard, high-volume system on its own. The goal then was to create the best possible beam expander to preserve those characteristics and allow a modular, simple design for the overall large aperture systems.

Expanding the beam: on-axis or folded?

Off-axis fold mirrors that many beam expanders use can change the polarization of the light. With high-power laser optics, and many other applications, polarization has to be known and, in fact, changed from measurement to measurement for full component characterization. Making the beam expanders on-axis means the optical axis of the interferometer engine itself is centered on the optical axis of the beam expander. This design choice proves important for both polarization considerations and for versatility.

Kinematics save realignment

With an on-axis kinematic mount for the standard Fizeau interferometer on the beam expander, the small-aperture engine can be readily removed and used for high-resolution, small-field-of-view measurements and then it can be replaced for measuring the full 600mm aperture—without realigning the system.

Furthermore, with the AccuFiz connected only to the beam expander—and no parts hard-mounted to the underlying air table—the entire system is simple to install and to move. In comparison, the custom 24" systems produced for the NIF program took 1 to 2 weeks to fully install and qualify, but 4D's new 24" system design can be unpacked and running in just a few hours, with full qualification in several days, limited mostly by the time required for long-term stability tests.

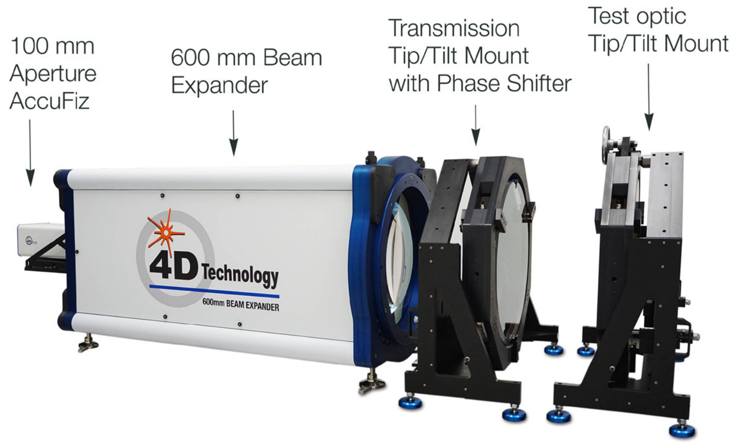


Figure 1: Overall mechanical layout of the 600mm aperture laser Fizeau.

Stability: Thermal, Resonance and Sag

The beam expander is one of the most critical elements of the system. As a 600mm collimator is quite heavy, deformation from thermal loads must be minimized to ensure mounting the optic doesn't misalign the lens.

To prevent ambient vibration from adversely affecting system performance, a resonance frequency of over 50 Hz is typically desired. Thermal effects should be modeled to guarantee proper operation in standard laboratory environments.

In an example of the improvements to be gained, for the 4D 24" system:

- Extensive CAD modeling determined the best materials and geometry for the design. Carbon-fiber materials were chosen for the support columns and specialized connecting elements, contributing to stability while keeping weight low.
- Resonance: The natural frequency of the structure was pushed above 50HZ
- Thermal stability: total length change was brought to below 10 µm over the 2m structure within a 10C temperature shift, creating unprecedented immunity to the ambient environment.

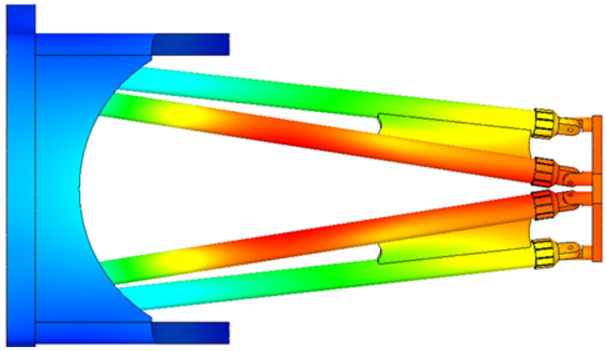


Figure 2: CAD Model output of static deformation under load. Red areas are the most deformed, but exhibit under six micrometers of total change in the 2m long structure. The curved elements connecting the support columns are critical for best performance.

Figure 3: A monolithic design means the entire system can be moved and shipped without disassembly.

Ensuring flexibility and ease of use

Incorporating several other mechanical design considerations will maximize ease of use and flexibility of a system. If phase shifting is accomplished by mechanical phase shift of a PZT, no recalibration will be necessary when the cavity is changed. This is an advantage versus wavelength-shifting interferometric systems. Also, mechanical phase shifting means the standard laser can be readily swapped with a variable-coherence laser via a fiber port on the 4” AccuFiz engine. With a variable-coherence source, the interferometer is able to measure plane-parallel optics without any effects from the back-side reflection from the optics. With this interchange-ability, homogeneity and other measurements are much simpler than is the case on most interferometric systems.

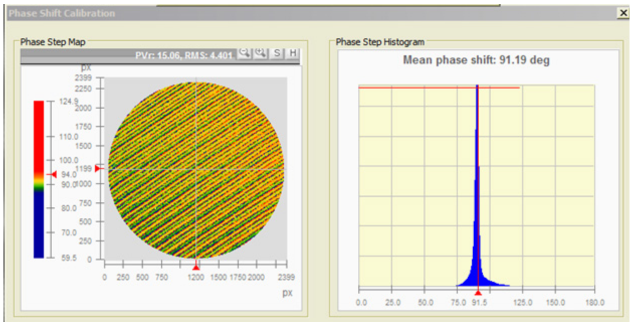


Figure 8: Using a mechanical phase shifter creates a very narrow phase shift variation across the entire aperture.

Mechanical separation of external optics

Separate the transmission flat and phase shifter mechanically from the rest of the structure. This makes swapping elements for a 3 flat test very simple and, for different tests, the cavity between the transmission flat and return flat can be readily reconfigured. To minimize stress, pressure and gravitic distortion, mount the flats themselves in an ultra-low-stress system. Large optics are particularly sensitive to these effects. The 4D system uses a double-chain mount, which allows for rotation of elements for 3-flat tests while ensuring minimal stress is placed on the optics. Thereby, interferometer accuracy is maximized.

Make alignment as easy as possible

Alignment can be difficult in a multi-lens system. A high-power alignment laser on a positioning gantry, which is hard-mounted to the front of the system, is able to be positioned anywhere within the field of view. Using the alignment laser, lining up optics for test is simple and quick, minimizing potential damage from handling such large, expensive elements.

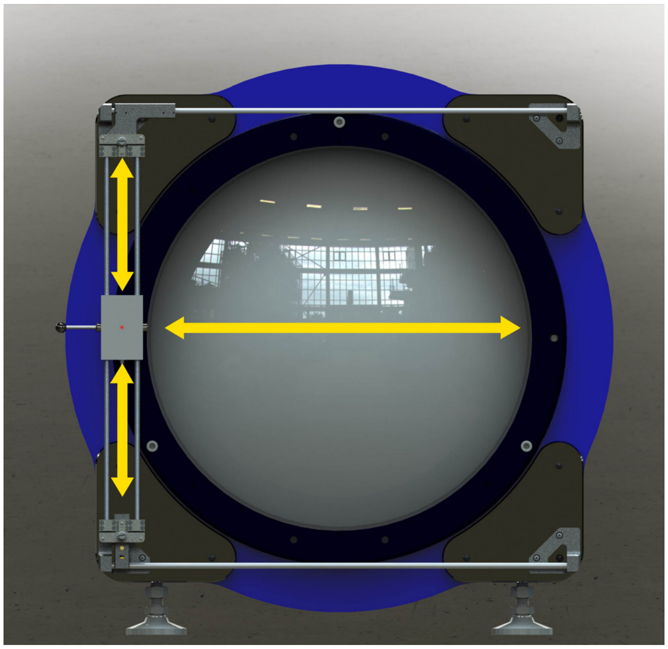


Figure 4: Gantry-type alignment laser setup. The gray rectangle contains an alignment laser that can moved to any part of the 600mm aperture

Optical performance

Optically, several items are of critical importance. Foremost is the overall quality of the cavity formed by the return flat and transmission flat, which ultimately determines the base accuracy of the interferometer. While a lower-quality cavity can be compensated via a 3-flat test, the better the cavity is at root, the better the final results will typically be. Plus, a 3-flat test requires a second transmission flat, which is not always within a customer's budget.

4D Accufiz example results: With no off-axis elements, optimal lens design and the mechanical design choices shown above, the system was able to achieve better than lambda/20 peak-to-valley cavity quality for a 1064nm wavelength, 600mm aperture.

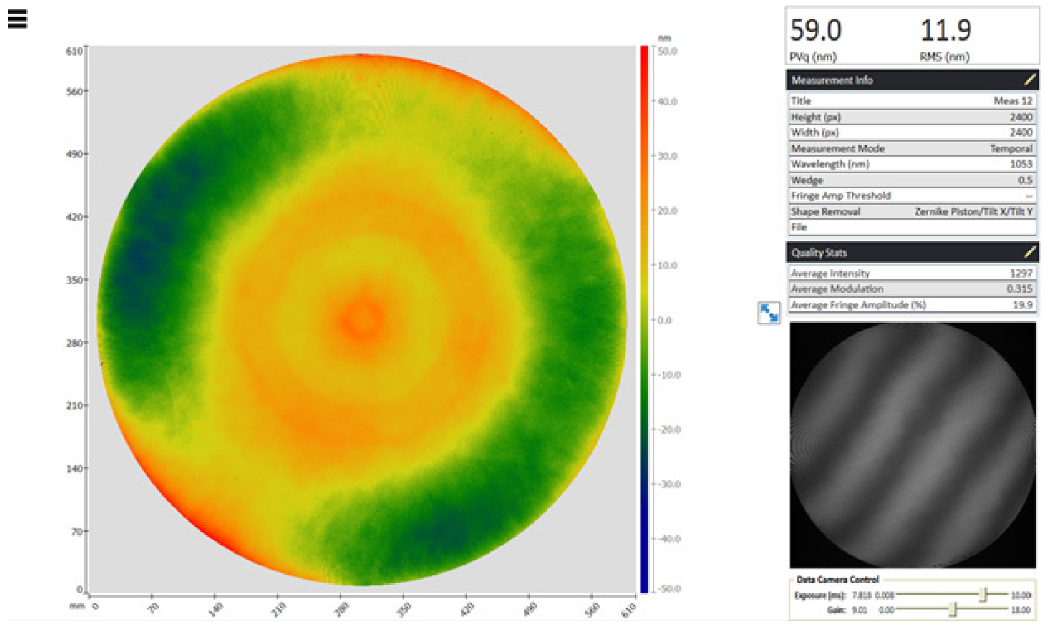


Figure 5: Cavity quality is better than lambda/20 peak to valley in this 1064nm wavelength 600mm interferometer.

Assuring quality of the cavity

The two critical limiters for characterization of contemporary precision optics involve the spatial frequency response of the interferometer system, and assuring best focus when measuring a component.. A poorly designed system will not properly measure high-frequency components, and even a well-designed system may produce erroneous data if the test optic is defocused. Also, if there is high-frequency structure in the optics of the interferometer itself, that surface structure can undermine the ability to measure such structures in the test pieces.

Focus

Best focus is essential to high resolution measurements, but is troublesome for a user to determine without aids. To guarantee proper performance, an autofocus routine whereby the system automatically determines best focus on any element they are measuring eliminates inadvertent variability. In 4D's software, the algorithm examines the contrast of an intensity step within the field of view, compares it to the theoretical result, and changes focus until the two most closely match.

Verifying the Instrument Transfer Function

Once best focus is achieved, one should be able to automatically calculate and display the Instrument Transfer Function (ITF). ITF is a graph of how well the measured results will compare to ideal structures of a given frequency. 4D's 600mm aperture system achieves 70% fidelity to beyond 2 lines/mm of spatial frequency, readily exceeding the performance of any other systems of this aperture size.

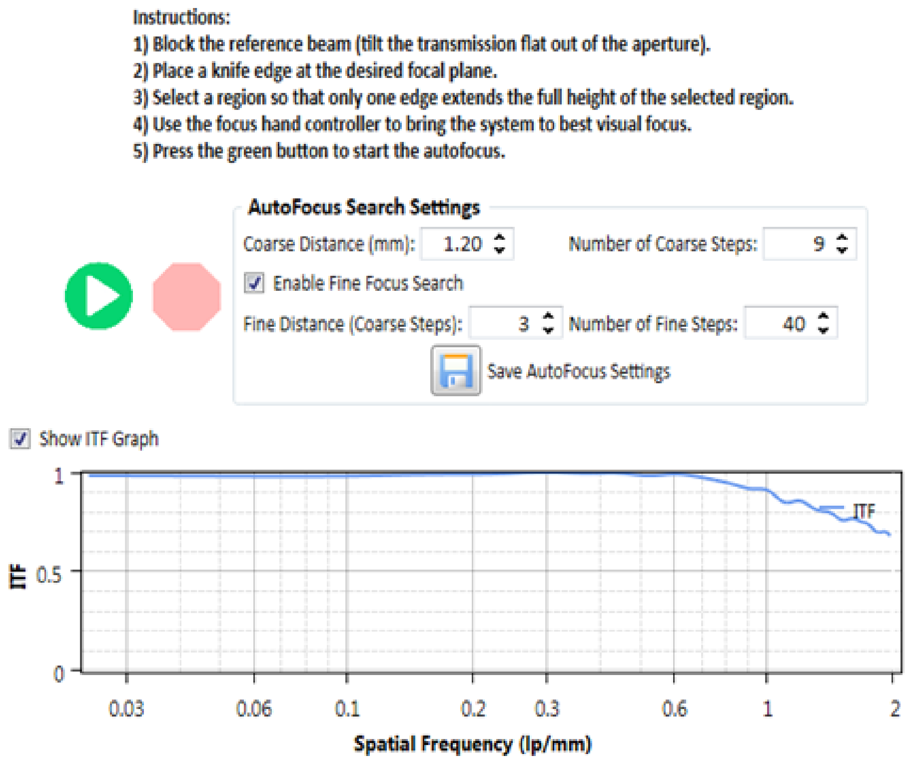


Figure 6: Autofocus function and automatic ITF plot ensure the highest quality measurements for any given setup.

Software: Gathering and analyzing data

Robust acquisition and analysis software must be built into the system.

Software should calculate the Power Spectral Density(PSD) of measurements. Many optical systems, but particularly high-power laser systems, are susceptible to structures of certain spatial frequencies, mostly of higher frequency, and therefore component manufacturers must ensure such structures are not present. For example, 4D's original 600mm system—destined for use in high-power laser applications—was required to have no structure in the basic cavity measurement above a frequency of $0.1\gamma^{-1.55}$ from frequencies of 0.1 lines/mm to 0.4 lines/mm. The software allows entry of the trendline equation and calculates the PSD over the full range. Results showed that the system exceeded the specification, ensuring proper operation in each measurement with minimal user overhead.

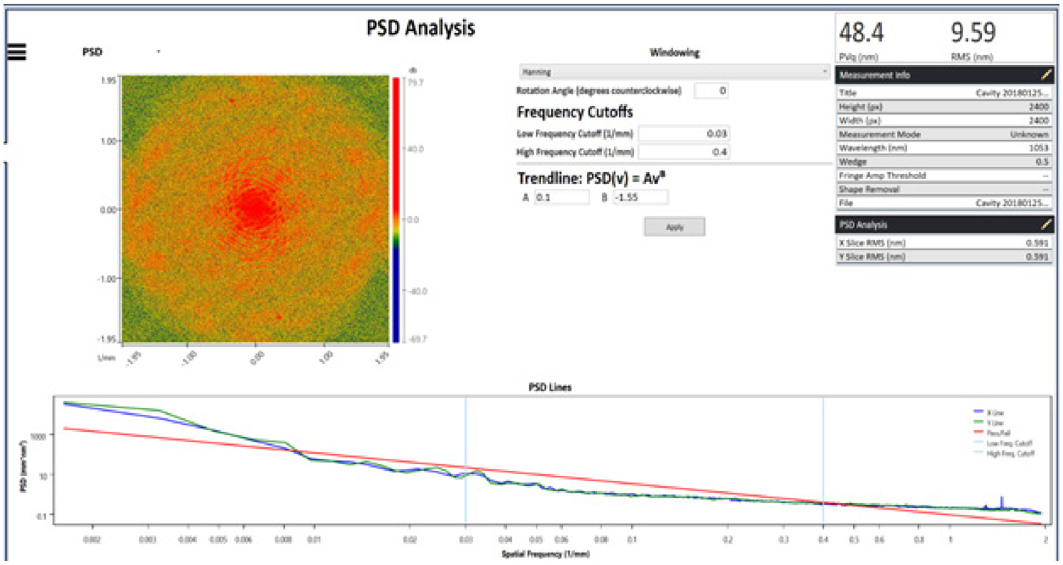


Figure 7. Software calculation of PSD.

Conclusions

In general, improvements in interferometry over the past few decades have come from advanced software that improves phase unwrapping, speeds measurements, and provides additional analysis capability.

But to further advance the state of the art of interferometry, then modern modeling of mechanical design, carefully considered materials selection, and a user-centric approach to hardware design are critical.

Incorporating diagnostic tools for visual representation of the calibration quality, automatic calculation of the system ITF, and measurement PSD will give users confidence that one's measurement quality is meeting specification each and every time.

Providing capabilities such as easily-switchable laser source modules, high-powered alignment beams, and autofocus significantly improve ease of use and minimize time-to-results. These capabilities guarantee that resources can be devoted to optimizing optical fabrication, instead of setting up measurements.

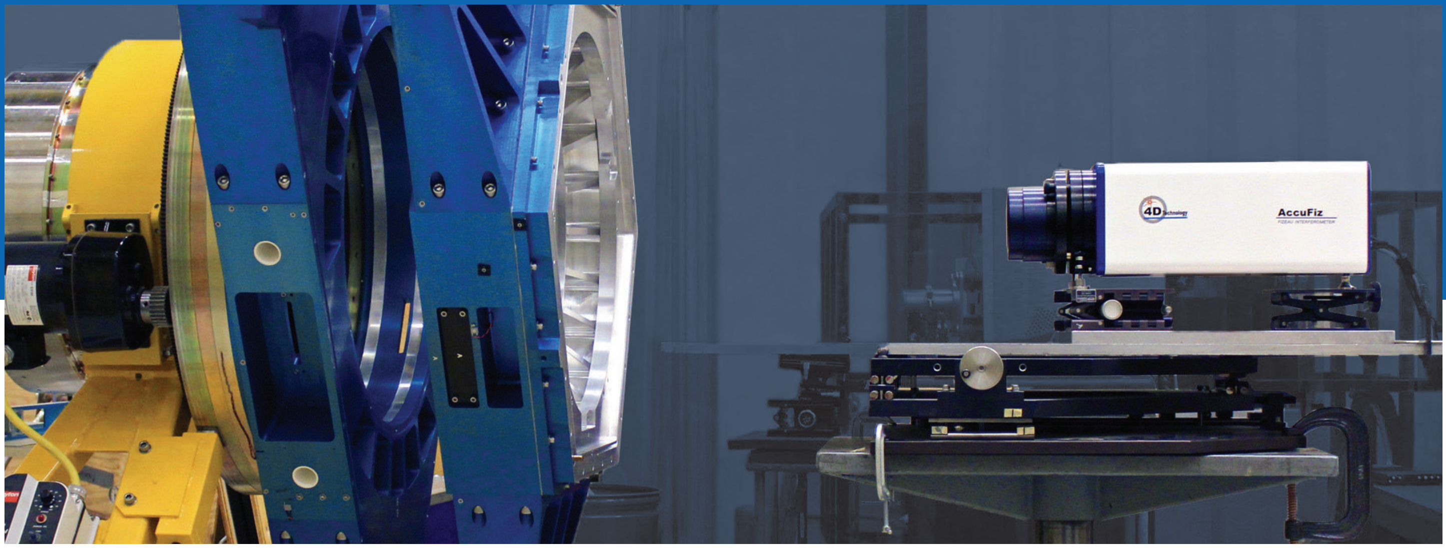
Perhaps most important, because of the universality of the elements described in this white paper, one may insist that they apply not just to the largest systems, but to one's entire range of Fizeau interferometer aperture sizes. This would ensure the best capabilities, no matter the part under test.

About the author

Dr. Erik Novak is Director of Business Development at 4D Technology. He received his PhD in Optical Sciences from the University of Arizona in 1998 under Dr. James Wyant.

He has been developing metrology instrumentation for more than 24 years.

Measure well, no matter how big the project gets



Vibration-Insensitive AccuFiz Interferometer at NOAO's Optics Shop facility, shown here measuring components for the WIYN telescope's One Degree Imager. AccuFiz is available in a full complement of source wavelengths, and apertures. It can be configured with or without vibration-insensitive dynamic measurements.

Download the data sheet:

Click here for the
AccuFiz interferometer
Data Sheet

Get the surface and wavefront data you need, with highest precision, versatility, speed and ease of use. Only 4D offers short coherence interchangeable sources, dynamic measurements in turbulent environments, and lightweight, large aperture Fizeaus.

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