Intellium™ H2000 **Overview**

The ***Intellium™ H2000*** interferometer from ESDI is a unique interferometer based on a Fizeau geometry that is capable of taking measurements in the presence of vibrations and other environmental disturbances with virtually no compromise. Piezo or wavelength phase-shifting interferometers acquire multiple interferograms sequentially over time to create a single wavefront map of the part under test. The time involved to make the measurement allows vibration, mechanical drift, or air thermal currents to introduce errors. Other interferometers acquire a single interferogram that have a significant amount of tilt introduced. This tilt acts like a spatial carrier that can be used to reconstruct the wavefront. However, this method can introduce aberrations (mostly coma) that need to be calibrated out. Also the carrier method cannot be used for highly aberrated parts due to the local fringe densities exceeding that of the Nyquist limit. There are some polarization based phase-shifting interferometers on the market that solve the vibrations problems quite well for many applications, but have some compromises such as utilizing a non-common optical path which introduces some retrace errors. Other polarization based interferometers have a common optical path using non-coherent sources which work very well for measuring flats and films over short distances, but cannot be used for long distance measurements.

The ***Intellium™ H2000*** interferometer, from ESDI, uses a coherent laser source and polarized light as a principle of its operation in a common path Fizeau interferometer. The design solves many of the problems associated with other systems. The H2000 generates three phase-shifted interferograms simultaneously. The three interferograms are recorded at the same time by three independent cameras. In order to generate multiple interferograms it is required that reference and test beams be orthogonally polarized. To achieve this, a Fizeau interferometer layout has been modified by creating two spatially separated and orthogonally polarized sources. As shown in Figure 1A, two orthogonally polarized beams originating from two sources within the interferometer propagate out through the interferometer’s collimator at a slight angle.

The two beams reflect from a transmission flat (or sphere) mounted outside the collimator and from the measured object. The transmission optic and the object are tilted in such a way that they reflect two orthogonally polarized beams along the optical axes of the optical system of the interferometer. The remaining two beams reflected by the transmission optic and the test object are blocked from entering the interferometer by a spatial filter placed in the focal plane of the interferometer. This arrangement is illustrated in Figure 1B. Note that in order to reflect two orthogonally polarized beams along the optical axis of the interferometer the transmission optic and the test object must be slightly tilted with respect to each other. However, both reference and test “return” beams follow back through the optical system of the interferometer along a common path. This is important to minimize interferometer retrace errors.

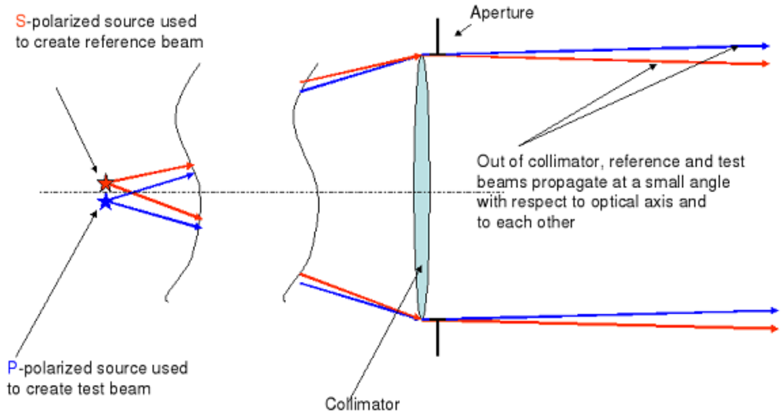


Figure 1A. Illuminator portion of a simultaneous phase shifting Fizeau interferometer.

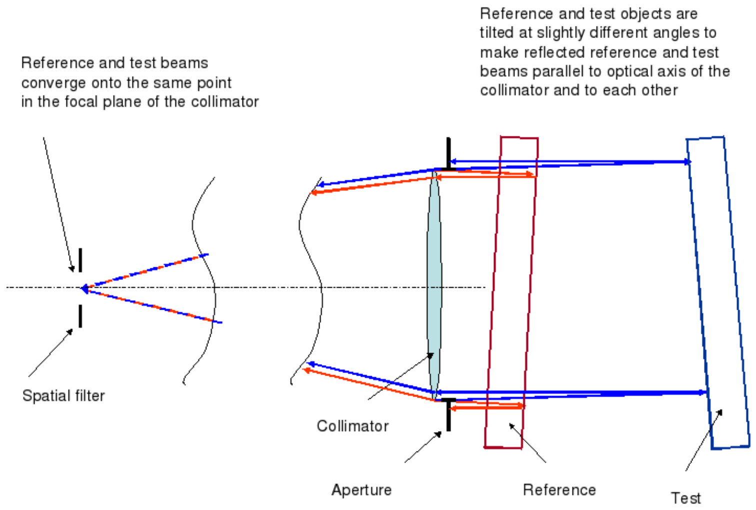


Figure 1B. Arrangement of the transmission flat and the measured object in the simultaneous phase shifting Fizeau interferometer.

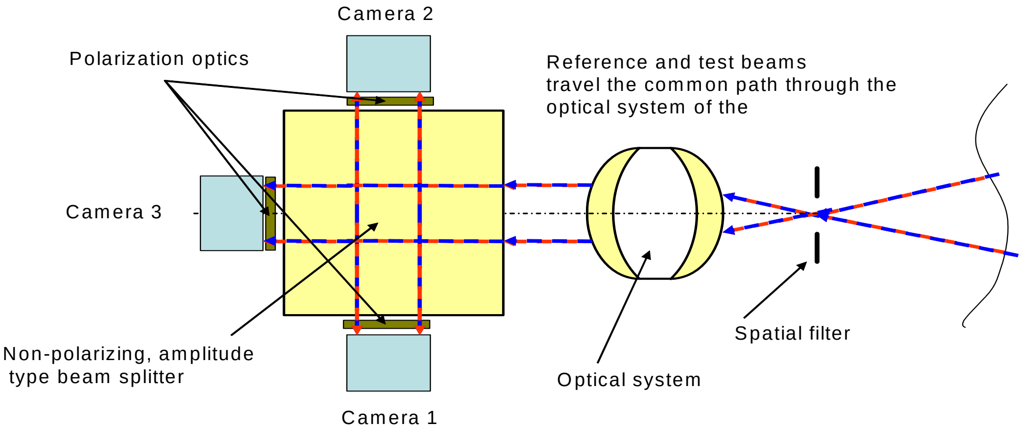


Figure 1C: Diagram showing the optical path and layout of optical elements inside the simultaneous phase shifting Fizeau interferometer.

Real-Time Phase Shifting

In order to generate three independent interferograms, the test and reference beams are split at the same rate into three channels in a special module that replaces the standard camera in the H2000. In each channel, phase delays are introduced independently in a controlled fashion so that the phase shifts between the interfering beams are set to 120^0 between consecutive interferograms. The three interferograms are captured simultaneously and transferred to the computer. The exposure time to capture the interferograms is typically 0.25 ms, but can be as low as 10us, and is limited only by the amount of available light and the capabilities of the cameras. Note that splitting the incoming beam into three channels does not violate the principle of the common optical path as the two interfering beams are split the same way and they traverse the same optical path all the way to the detectors. Figure 1C illustrates the beam arrangement inside the interferometer.

<u>Note:</u> Although the H2000 uses three cameras, they are sub pixel aligned and monolithically bonded together along with the beam splitting and polarization optics into a package smaller then two decks of cards stacked on top each other. The result is a rigid camera system similar to high-end 3-Chip color cameras with lifetime alignment. The advantage of using three cameras is that each of the interferograms retains the true resolution of the camera.

Measurements

Although the H2000 is a modification of a Fizeau interferometer it has certain characteristics that make it different from standard temporal phase shifting instruments:

1. The interferometer collects the interferograms in a very short time. This allows capturing measurements in the presence of vibrations, air turbulence, etc. This however does not eliminate the influence of air turbulence on the measurements. Since air turbulence and other similar disturbances are stochastic processes they can be eliminated from the measurements by averaging a certain number of them. Usually combining 8 to 16 measurements is sufficient to obtain good, repeatable results but in reality this number will depend on the severity of these disturbances and the required quality of the measurement. In fact, the presence of vibrations increases accuracy of the measurements by reducing the probability of systematic errors.

2. As the test and reference beams are orthogonally polarized it is possible to adjust their mutual intensities. This allows high contrast of the interference fringes for a large range of reflectivity of measured surfaces (from 0.1% to 100%) without the need to replace the reference elements or use of attenuating pellicles.

3. As the H2000 interferometer uses polarized light, it is sensitive to measurements of objects that may change the state of polarization of the illuminating beams. Thus measurements of birefringent parts, parts coated with polarization altering coatings, surfaces illuminated at shallow angles, as well as other similar cases may be difficult or even impossible. Depending on the external optical system there are often solutions to this, such as adding an external polarizer or waveplate to reorient the incoming polarization.

4. Two beams leaving the interferometer propagate through the collimator lens at a slight angle with respect to each other (for H2000 the angle difference is 3.6mrad). This asymmetry causes a small violation of the principle of a common optical path (for the out-going beams) and results in small aberrations being added to the measurement. This error is a function of the angle between the two beams and the optical design of the collimator lens. In case of measurements with transmission spheres, this error will be slightly higher. However, this error can be completely eliminated by taking two measurements with the role of the two illuminating beams being reversed (i.e. if the first measurement is made with the P-polarized beam reflecting from the reference optic and the S-polarized beam reflecting from the test object, the second measurement should be done with the polarizations reversed). One of these measurements is inverted and averaged with the other in software, resulting in complete cancellation of these types of errors. With the assistance of ASML, ESDI has demonstrated and documented H2000 instrument errors to be less than λ/100.

Accessories

The H2000 interferometer is capable of taking measurements of flat as well as spherical surfaces. The beam diameter is 100 mm and the instrument accepts all industry standard 4” (100mm) bayonet mounted reference optics.

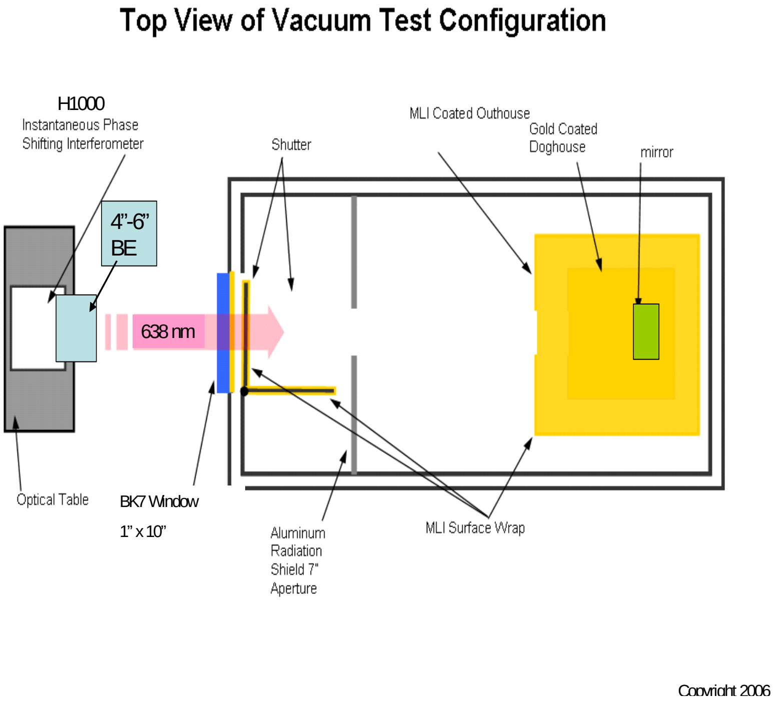
Comparison to Other Types of Real-time Phase-Shifting

1. Fizeau Design
    a. The H2000 is the only coherent laser based interferometer capable of producing measurements equal in accuracy to a classical Fizeau common path interferometer. This is due to the H2000’s patent pending dual beam technology.
2. Spatial Carrier Methods
    a. Spatial Carrier methods use a significant amount of tilt between the test and reference beams to generate a spatial phase-shift in a single interferogram. Since only one interferogram is used, vibration insensitivity is achieved. But the tilt generates coma aberrations which must be calibrated out. Also this method does not allow large local slopes to be measured. This means heavily aberrated optics cannot be measured.

Measurements in a Vacuum

We will now show three real-world applications where the ***Intellium™ H2000*** capabilities are essential.

Figures 2A and 2B, show interferometric measurements made through a vacuum chamber. The goal was to achieve the highest possible measurement RMS repeatability of a mirror while cycling the vacuum pressure from ambient to 10^{-6} torr. Note that the interferometer is positioned outside of the vacuum chamber on a wheeled cart with no vibration isolation. The results of these measurements as quoted by *SSG Precision Optronics was "Good repeatability (rms < 1/1500 w) in extreme cryogenic vacuum chamber conditions" (see Figure 2C).*



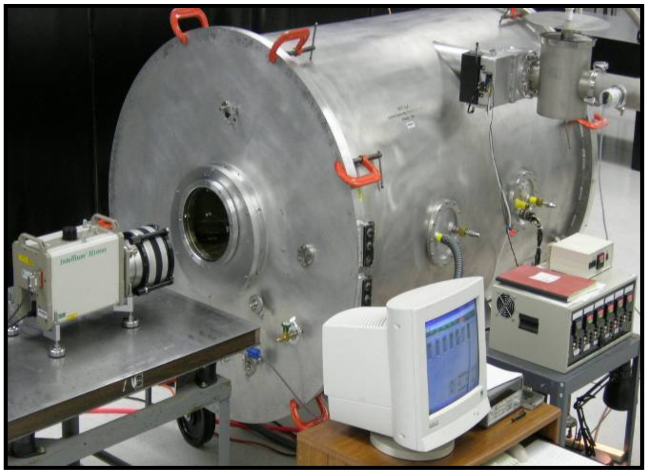


Figure 2B: Vacuum chamber setup with an H2000 simultaneous phase-shifting interferometer.
Courtesy of SSG Precision Optronics

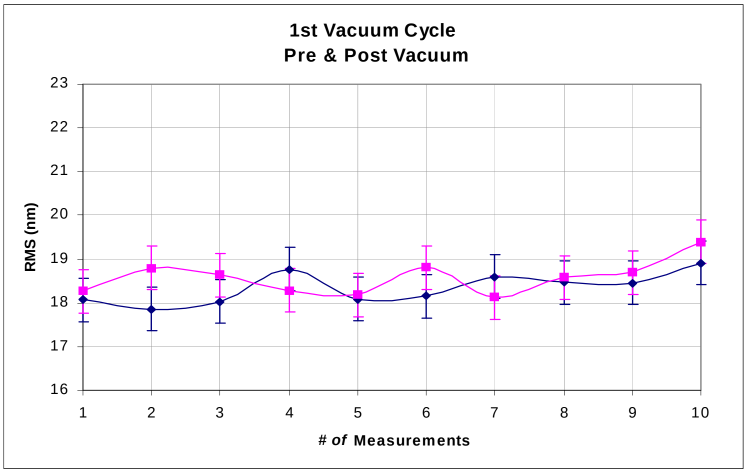


Figure 2C: RMS of measured wavefront while cycling the pressure in a vacuum chamber from ambient to 10-6 torr.
Courtesy of SSG Precision Optronics.

Measurements in Vibration and Atmospheric Turbulence

In the past atmospheric thermal effects have been a major hindrance to measuring good optical wavefront for larger optics. This is because changes in air temperature and pressure in the interferometer's beam path cause distortions in the fringe pattern. If these distortions are random over time they can be averaged out, if the acquisition time to capture a single wavefront is fast enough. With simultaneous phase-shifting this is now possible. Figure 3A shows the ***Intellium™ H2000*** measuring a 1.5 meter mirror six meters away. The thermal currents can easily be seen by subtracting two consecutive wavefront measurements. If these currents vary slowly then it becomes difficult to average them out as seen in Figure 3B (lower left). A fan can be used to mix up the air in order to randomize these currents, allowing them to be averaged out as seen in Figure 3B (lower right). The mirror's final wavefront can then be measured accurately as shown in Figure 3B (upper right). These types of measurements have so difficult to make in the past, some customers have responded with their new found capabilities as follows: *"We are using the **Intellium™ H2000** every day and are ecstatic. We would like to acquire at least one more." Optical Surface Technologies LLC.*

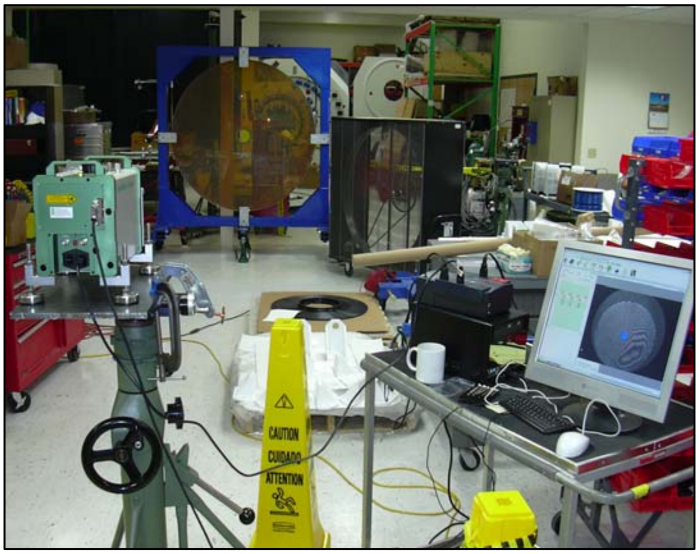


Figure 3A: The H2000 interferometer (left) measuring a 1.5 meter mirror (in the far back to the left). A fan (in the far back to the right) is used to mix up the air, removing static thermal currents. The monitor on the right shows the interferogram. *Courtesy of EOST, Tucson AZ.*

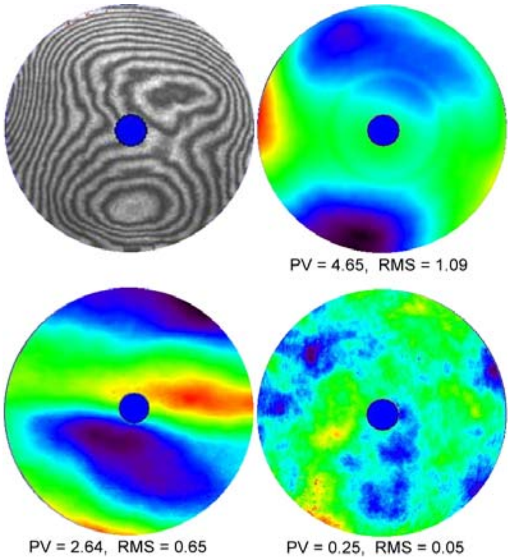


Figure 3B: Wavefront data (upper right) of a 1.5 meter mirror acquired in heavy vibrations and a turbulent atmospheric environment. One of three interferograms is shown in the (upper left). The static thermal currents seen in the lower left are randomized by a fan resulting in random thermal pockets (lower right).

Mission Critical Space Optics

Many times scientists do not have the luxury of measuring mission critical space optics in well behaved laboratory setups. The H1000 is being used to measure the beryllium mirrors of the James Web Space Telescope (JWST) at Ball Aerospace Corp. For measurement, the mirrors are mounted in configurations similar to how they will be mounted in the actual telescope. This allows the effects of stress and other factors to be incorporated into the wavefront measurement. In the past, these types of measurements were impossible due to instability and vibrations. With the ability to acquire wavefront data in a matter of milliseconds in these simulated environments, the performance of these telescopes have a much better chance performing as expected in space. Because of this Ball Aerospace as quoted "*We currently have an* ***Intellium™ H1000*** *and a MiniScatR™. Over the next 2 years we may buy several more systems."*

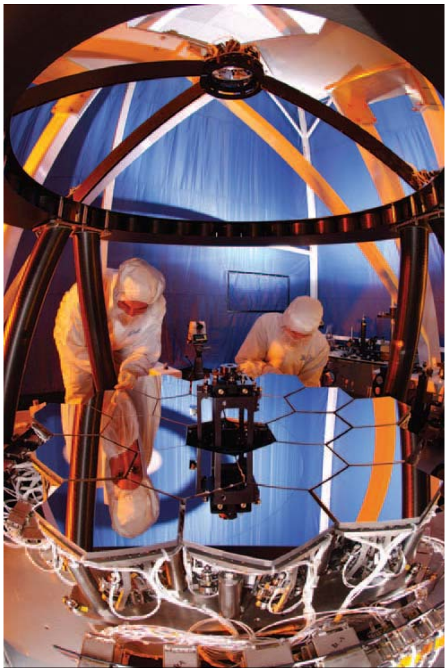


Figure 4: James Webb Space Telescope Primary Mirror (1/6 actual size). *Courtesy Ball Aerospace & Technology Corp.*

Large Optical Measurements with a Remote Fizeau Cavity

Large optics are often difficult to measure due to the long optical paths lengths. Long optical path lengths allow many potential errors to be introduced into the measurements. The errors can be due to vibration, atmospheric turbulence, and mechanical drift of heavy parts. Although the ***Intellium™ H2000*** can handle these errors as mentioned previously, there is an additional elegant solution. A remote Fizeau cavity can be used, where the transmission optic (TR) and test optic are closely spaced from each other a remote distance away from the interferometer. Since the test and reference beams are orthogonally polarized, all phase-shifting is performed inside the interferometer even though the TR is positioned far away. A real-world example is shown in Figures 5A and 5B where both the TR and test flat are approximately 8.0 meters away from the interferometer. The 1.6 "test" meter mirror (lower mirror in Figure 5A) is being measured with a smaller 1.0 meter transmission flat (the remote Fizeau cavity). Since the transmission flat is smaller than the test flat, the test flat must be measured many times while being rotated. The overlapped measurements are then stitched together using ESDI's stitching software. This requires data to be acquired extremely fast to minimize errors as mentioned previously. Typical responses from customers requiring these types of measurements are as follows: *"ESDI's unique simultaneous phase shifting makes it possible to obtain good interferometric data in uncontrolled environments or even those that feature high vibration or high air-flow, such as that encountered while evaluating the thermal performance of an optical system." Raytheon Missile Systems.*

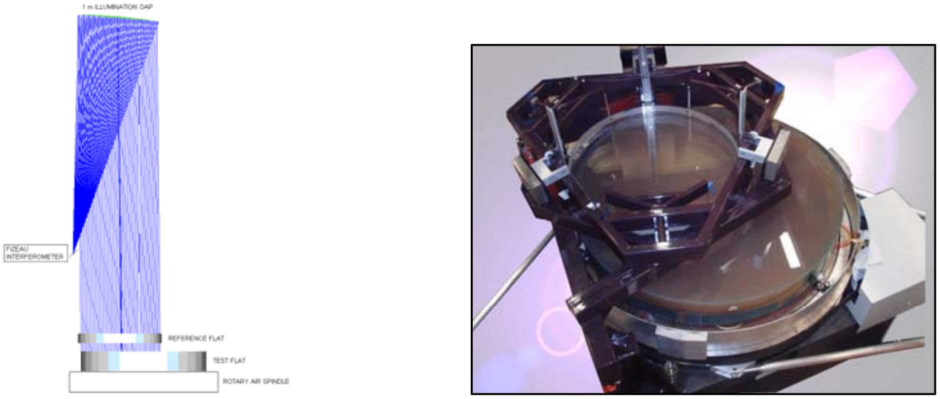


Figure 5A: Test Setup for measuring multiple apertures of a larger optic. On the left, the diagram shows the beam propagating from the interferometer (far left) to an off axis parabola (top left), then down to the transmission flat and test flat. In the right image, the top optic is the calibrated 1.0 meter transmission flat and bottom optic is the 1.6 meter test flat. The remote Fizeau cavity is the gap between these two flats. Courtesy of College of Optical Sciences (University of Arizona).

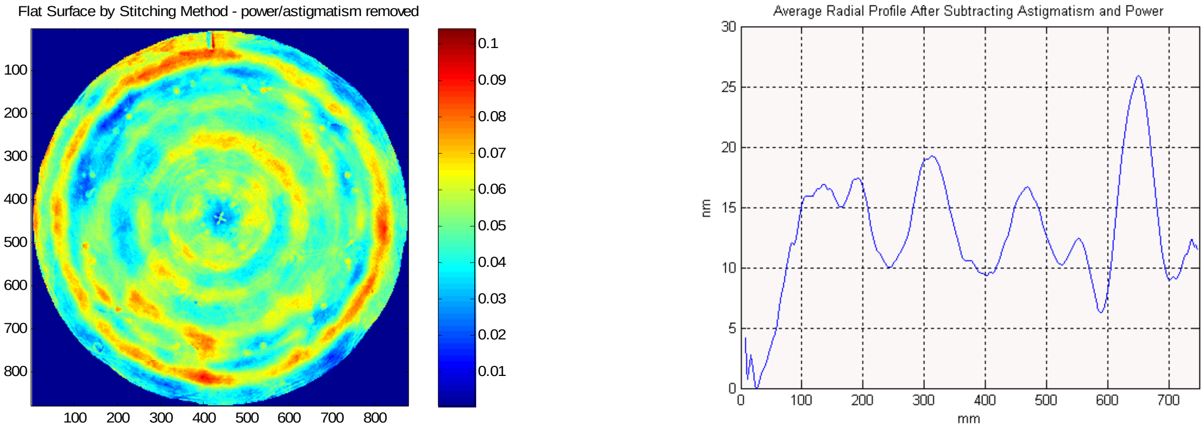


Figure 5B: Surface map of test optic (Figure 1) created by stitching 12 sub apertures. (left) and corresponding average radial profile (right). Surface irregularity from stitching – power and astigmatism removed. Final Result: 7.3 nm rms, 116 nm PV.

Conclusion

The ***Intellium™ H2000*** offers true vibration insensitivity, high interferogram resolution, and the advantages of a true common path Fizeau interferometer. Since the H2000 uses common Fizeau type accessories, it can easily be integrated into existing research and production systems.