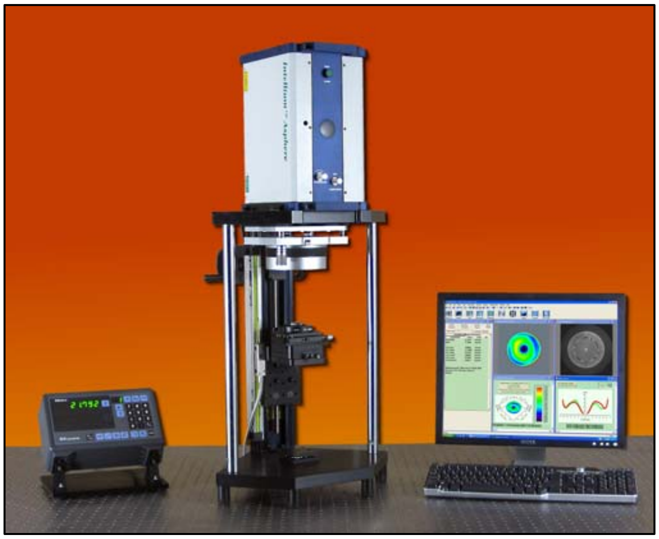
***Intellium™ Asphere* Overview**

Introduction

The ***Intellium™ Asphere*** is an interferometer based on Fizeau geometry intended for measurements of aspheric surfaces. Measurements are performed using standard spherical references. As a result of its innovative approach, the measurement process closely resembles that of spherical or flat elements. The unique features of the ***Intellium™ Asphere*** allow a wide variety of aspheric surfaces to be measured including standard axially symmetric parts as well as axially asymmetric and off-axis type surfaces. Parts with surface discontinuities like holes or grooves also pose no obstacle to the measurement process. Virtually any surface that can be mathematically defined and having slopes within the instrument's measurement range can be measured.



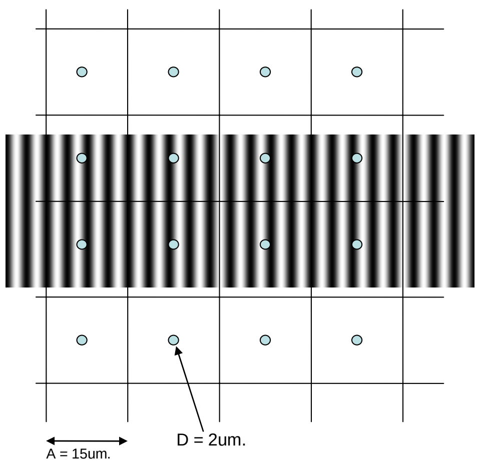
Overview

The ***Intellium***™ ***Asphere*** uses a **Computer Generated Reference**™ **(CGR**™**)**. ESDI's newly developed patent pending technology is combined with the Sub-Nyquist Interferometry (SNI) to overcome the limitations of existing conventional interferometric methods. The **CGR™** provides similar advantages to the measurement process as hardware methods of creating nulling references like Computer Generated Holograms (CGH) or Nulling Lenses. Therefore it is possible to perform measurements of aspheric surfaces by nulling fringes in the interferometer with the priceless advantage of generating relevant references in real-time to match virtually any asphere. This results in a significant increase in the range of measurement and amount of asphericity that can be measured for almost any type of surface with no increase of additional operations. This new technique is an extension of Phase Shifting Interferometry (PSI) and maintains the precision that is inherent to PSI. Other than a new type of camera in the interferometer, this method does not require any special hardware providing simplicity and robustness to the process.

Recording and processing high-density fringes

Interference of a test beam reflecting from a measured aspheric surface and the reference beam that reflects from the spherical reference leads to the formation of very dense fringes at the detector. To resolve these fringes, the ***Intellium™ Asphere*** uses a pixilated detector with an overlaid mask of pinholes – the so called "sub-Nyquist" detector - as shown in Figure 1. The resulting structure can resolve very high density fringes as it uses small-size pinholes as its sampling elements. However, in this kind of detector fringes will fall on the "dead" zones between neighboring pixels and will be lost and not processed. This property of the sub-Nyquist detector creates some difficulties and makes final unwrapping of the phase map more difficult but not impossible (see figure 1).

With the sub-Nyquist camera in the ***Intellium™ Asphere*** it is possible to process fringes with much higher densities than would be possible with a regular camera – fringe densities of up to 4 fringes/pixel are allowed making a maximum of 2000 fringes of tilt across the detector acceptable for processing.



Using a sub-Nyquist camera

The "sub-Nyquist" camera is a camera equipped with a pixilated detector with a pinhole mask placed on each pixel. For such a camera an important parameter: α is defined as:

$$\alpha = D/A \text{ is } \alpha < 1$$

This enables resolutions of fringe patterns that are more dense than the spacing between the pixels but allows more then one fringe between the pixels, resulting in generally unknown phase difference values between the neighboring pixels1,2.

Figure 1: Diagram illustrating operation of the sub-Nyquist detector. Fringes projected on the detector are sampled by the set of pinholes superimposed on the larger detector cells. Information about fringes falling onto the space between the pinholes is lost.

The interference fringes are sampled with a set of pinholes that are spaced by a distance corresponding to the pixel size of the camera. As the fringe density can exceed the density of the pixels the aliasing of spatial frequencies will occur in the recorded images. The aliasing will manifest itself in the form of Moiré fringes in the interferograms. This is depicted in Figure 2 where a series of interferograms is shown illustrating the appearance of interference fringes of a defocused spherical surface as a function of translation from the parafocal location.

The ***Intellium™ Asphere*** uses phase shifting technology to measure phase on a pixel-by-pixel basis, thus it can correctly calculate phase for each pixel including the areas of aliased frequencies. On the other hand, the unwrapping of the aliased interferograms is more difficult and requires a different approach than unwrapping of standard, non-aliased measurements.

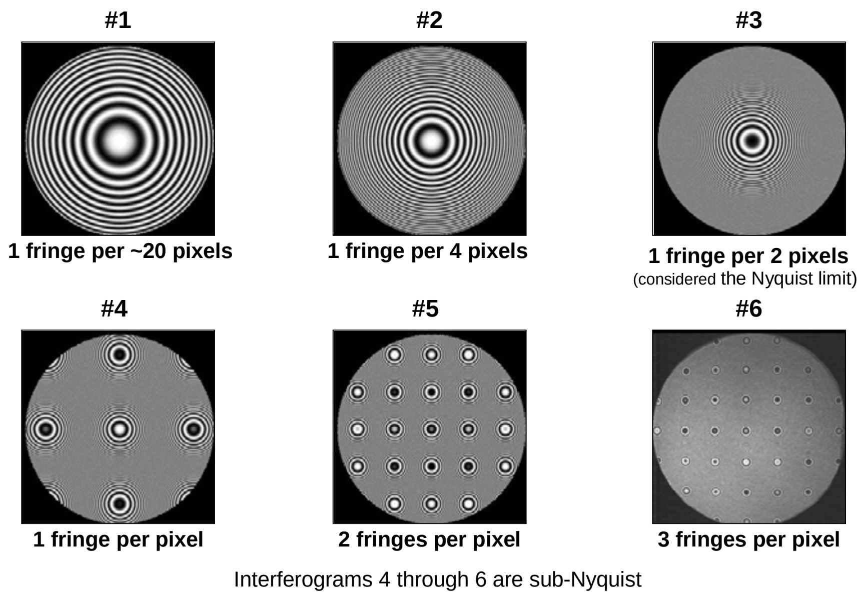


Figure 2: From top-left to bottom-right fringe density is increased. The bottom three images show aliased interferograms due to the Nyquist limit.

Processing the Aliased Interferograms

ESDI has developed new unwrapping algorithms capable of processing aliased fringes.
Figure 3A shows how standard PSI unwrapping methods would incorrectly unwrap an aliased interferogram, while Figure 3B shows how SNI unwrapping correctly unwraps the data. Figure 4 shows actual processed interferogram data from the new ***Intellium™ Asphere*** interferometer. Although this method already works well, ESDI has further developed patent pending technology that provides even better capabilities as described in the next Section.

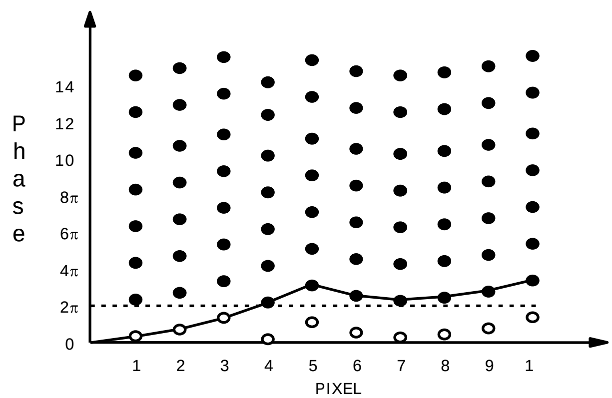


Figure 3A: PSI unwrapping failed.

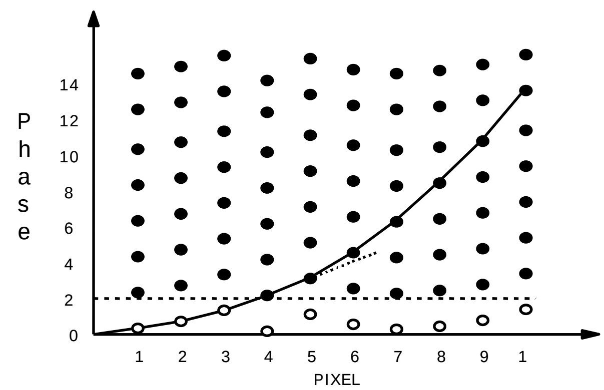


Figure 3B: SNI unwrapping successful.

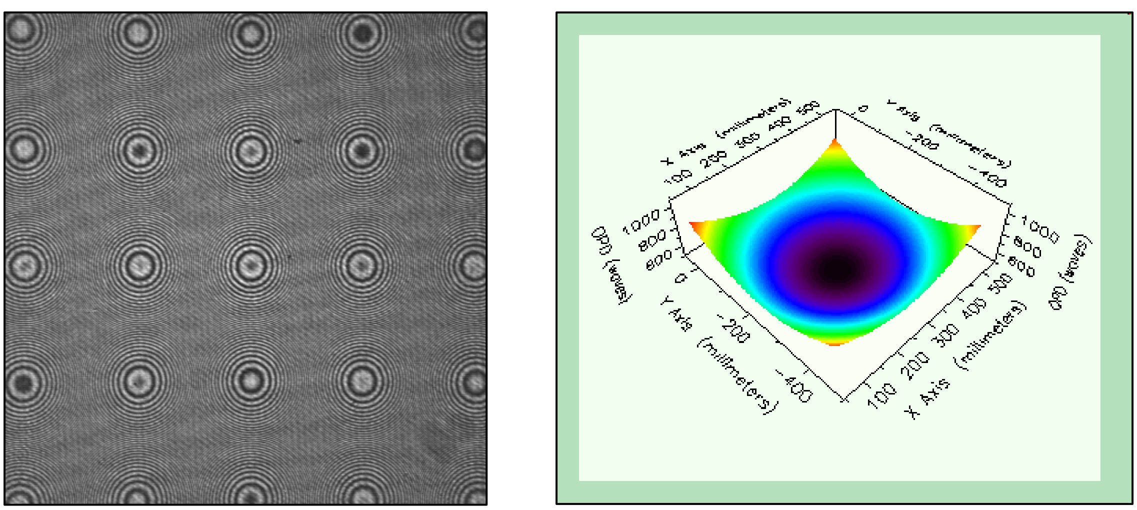


Figure 4: Highly defocused interferogram (left), and the resulting OPD wavefront (right).

Computer Generated Reference™ (CGR™)

The ***Intellium™ Asphere*** is a Fizeau type interferometer. Fizeau interferometers are popular because they are common path allowing errors introduced by the interferometer and transmission optics (except the reference surface) to be cancelled out when the fringes are nulled out. This advantage is lost when measuring aspheres because the wavefront propagation through the interferometer is different for the test asphere and the transmission sphere. Higher aspheric departures from a sphere introduce higher retrace errors. The ***Intellium™ Asphere*** has an elegant solution to this problem.

From knowledge of the interferometer, transmission sphere, and test asphere design, wavefronts can be traced from both the *reference* and *test optic* surfaces back to the sensor array. This results in two wavefronts that can be subtracted to generate a **Computer Generated Reference**™ **(CGR**™**)** as shown in Figure 5. If the *test asphere* matches exactly to the *asphere prescription*, then subtracting the **CGR™** should result in a flat wavefront. Thus, the **CGR™** can then be used to achieve near perfect asphere alignment and to reduce fringe densities well below the Nyquist limit.

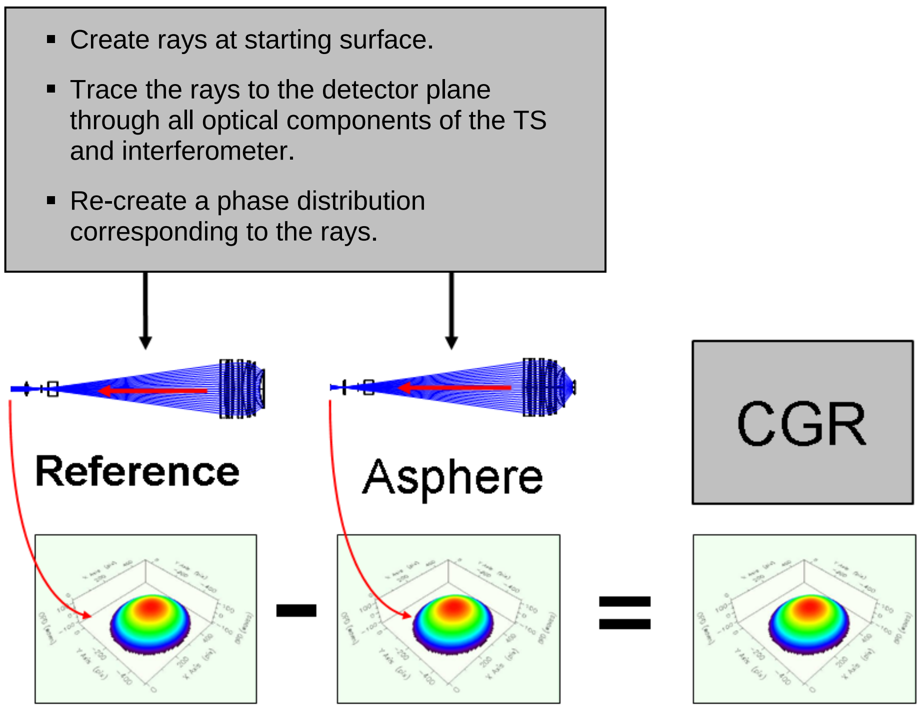


Figure 5: A **Computer Generated Reference™ (CGR™)** is calculated by subtracting a ray-generated transmision sphere wavefront from a ray-generated wavefront of the test

Generating the **CGR**™ requires the test optic prescription. To simplfy the generatation and use of a **CGR**™, a Asphere **CGR**™ Software Wizard has been developed as shown on Figure 6. The wizard allows the user to enter the complete asphere prescription which is maintained in a database for future use. The wizard then automaticly selects the optimum transmission sphere, measurement position along the optical axis, and then generates the **CGR™**. This **CGR™** is a constant, is unique to the asphere being measured, and can be saved for future measurements. Graphs of the OPD and surface slope are generated automatically for verification. Warning flags automatically warn the user if maximum slope or caustic conditions prevent proper measurement.

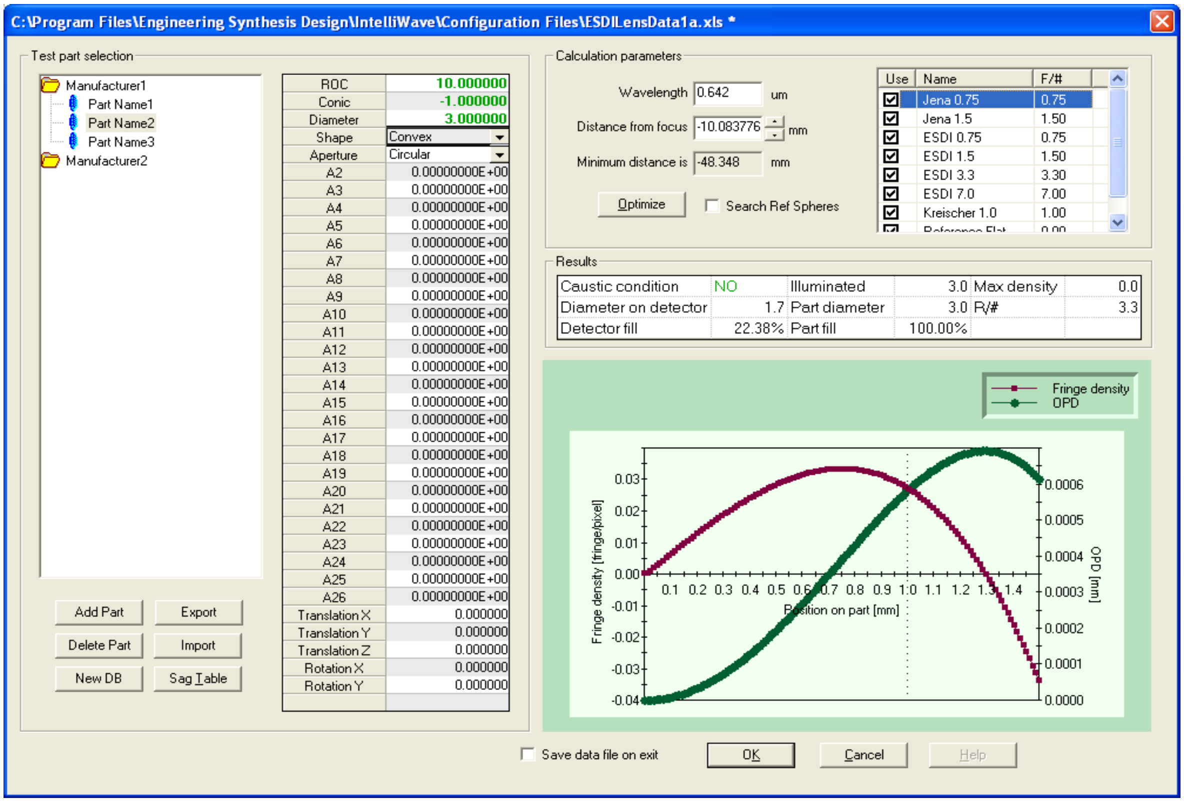


Figure 6: Generating a **CGR™** for a specific asphere requires the user to enter its prescription as defined in programs such as ZEMAX™. Standard aspheres and off-axis aspheres are supported. Free form surfaces require add-on software modules for defining the surface design figure. Graphs of the OPD and surface slope are generated automatically for verification. Warning flags automatically warn the user if maximum slope or caustic conditions prevent proper measurement.

Using the CGR™ in Making Measurements

The **CGR™** becomes a powerful tool in aligning the asphere test optic to the interferometer. Both **CGR™** OPD and **CGR™** interferogram wavefronts can be used in the process of making measurements. The **CGR™** interferogram is moire'd in real-time with interferogram video to produce real-time nulled interferograms. Thus in aligment video mode, the asphere can be aligned to the interferomter in the same way as a standard test sphere. After alignment, the data is acquired and processed in a similair way as a standard test sphere. The only difference is the Softare automaticly subtracts the **CGR™** from the measured data. Measurement time is only a few seconds. The entire measurment sequence is shown in Figure 7 with the results shown in Figure 8.

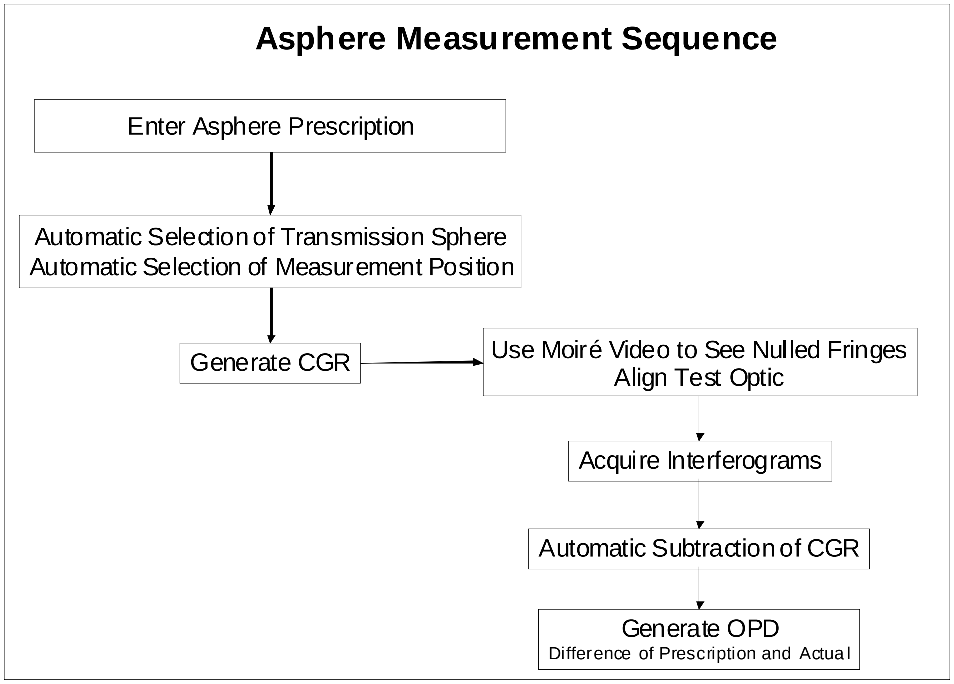


Figure 7A: Measurement sequence of measuring an asphere.

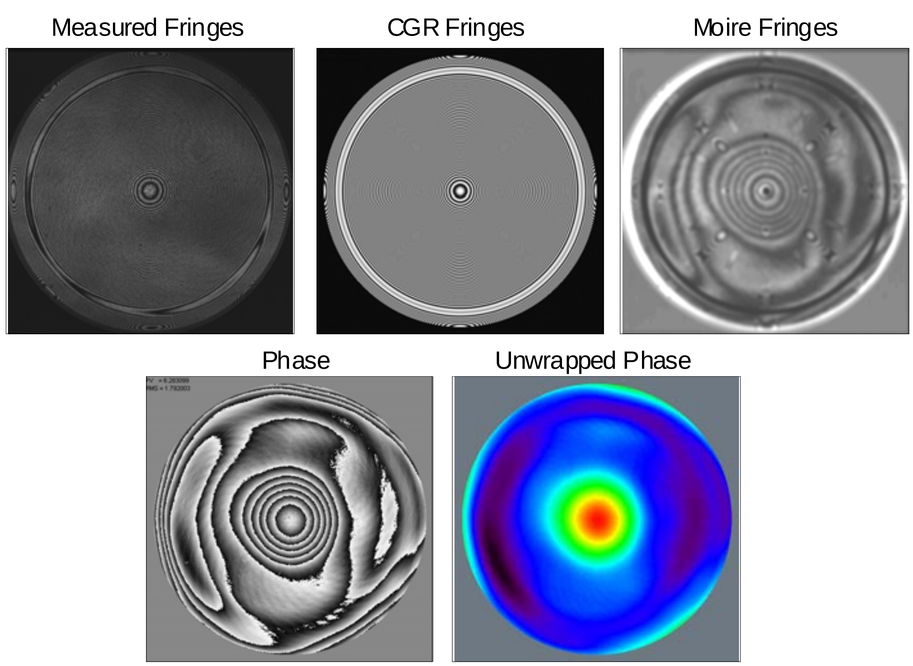
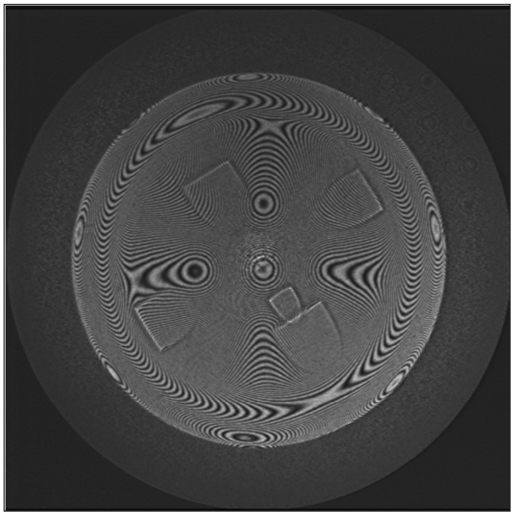
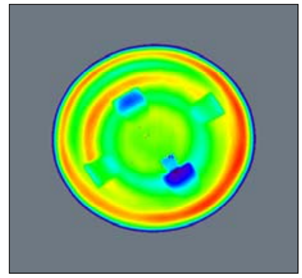


Figure 7B: Results of the measurement sequence shown in Figure 7A. The *measured* fringes are combined with the **CGR™** fringes to generate the *moiré* fringes. The phase and unwrapped phase are the result of subtracting the **CGR™** from the measured data.

Measurement Results

With the **CGR™** many types of aspheres can be measured that simply is not possible with other types of instruments including aspheres with holes, off-axis aspheres, and free form surfaces. This is because virtually any surface that can be mathematically defined can have an associated **CGR™** generated for it. In other words virtually any surface that can be mathematically defined and having maximum slopes within instruments range can be brought into a null fringe condition resulting in low fringe densities being processed. The following Figures show real world measurement results.

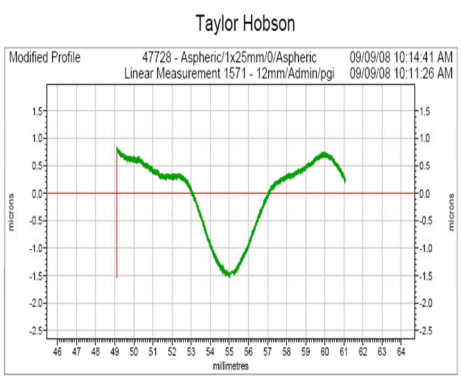




```
PV 99.90%     2.9529
RMS        0.5585

4) Focus     -0.2215
5) X Astig    0.1321
6) Y Astig    0.0695
7) X Coma     0.0435
8) Y Coma    -0.0521
9) Spherical -0.8191
```

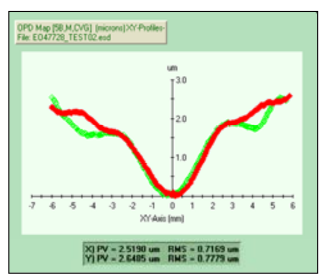
Figure 8A: Asphere with polished indentations.

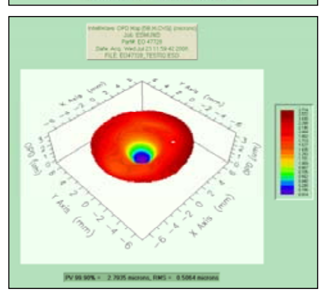


Rt	2.3898 µm		
Ra	0.5750 µm		
		Tilt	0.5430 °

Talysurf

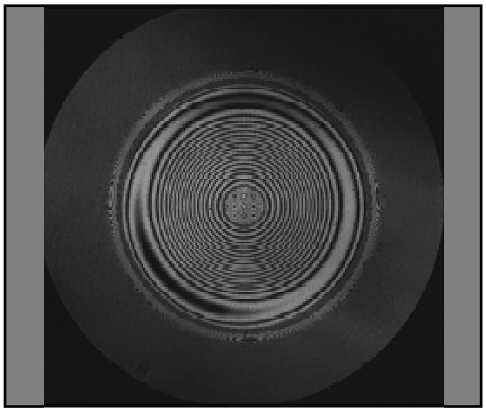
PV 2.3898 um,   RMS = 0.575

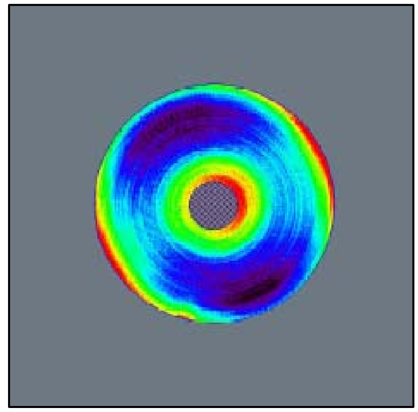


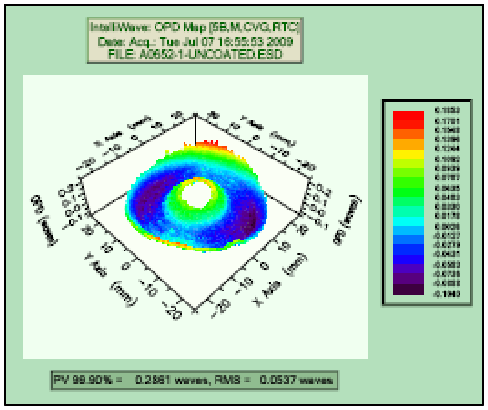


PV 2.519 um,   RMS = 0.7169

Figure 8B: ***Intellium™ Asphere*** measurement compared with Taylor Hobson measurement.

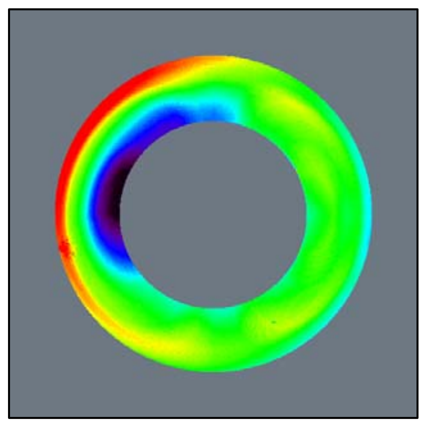


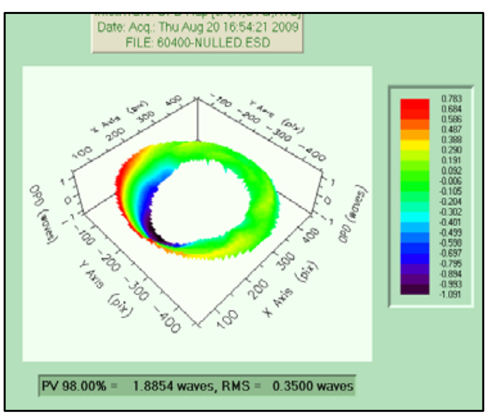




IntelliWave Report Summary			
Parameter	Value	Units	QC
PV 99.90%	0.2861	waves	
RMS	0.0537	waves	
4) Focus	-0.0152	waves	
5) X Astig	0.0446	waves	
6) Y Astig	-0.0598	waves	
7) X Coma	-0.0072	waves	
8) Y Coma	-0.0055	waves	
9) Spherical	0.1077	waves	
Date(measured): Tue Jul 07 16:55:53 2009			
Removed: X Tilt, Y Tilt, Focus			
Process: [5B,M,CVG,RTC]			

Figure 8C: Asphere with small hole





IntelliWave Report Summary			
Parameter	Value	Units	QC
PV 98.00%	1.8854	waves	
RMS	0.3500	waves	
4) Focus	0.7707	waves	
5) X Astig	-0.0999	waves	
6) Y Astig	-0.0393	waves	
7) X Coma	-0.5637	waves	
8) Y Coma	-0.1795	waves	
9) Spherical	-0.3065	waves	
Date(measured): Thu Aug 20 16:54:21 2009			
Removed: X Tilt, Y Tilt			
Process: [5A,M,CVG,RTC]			

Figure 8D: Asphere with large hole.

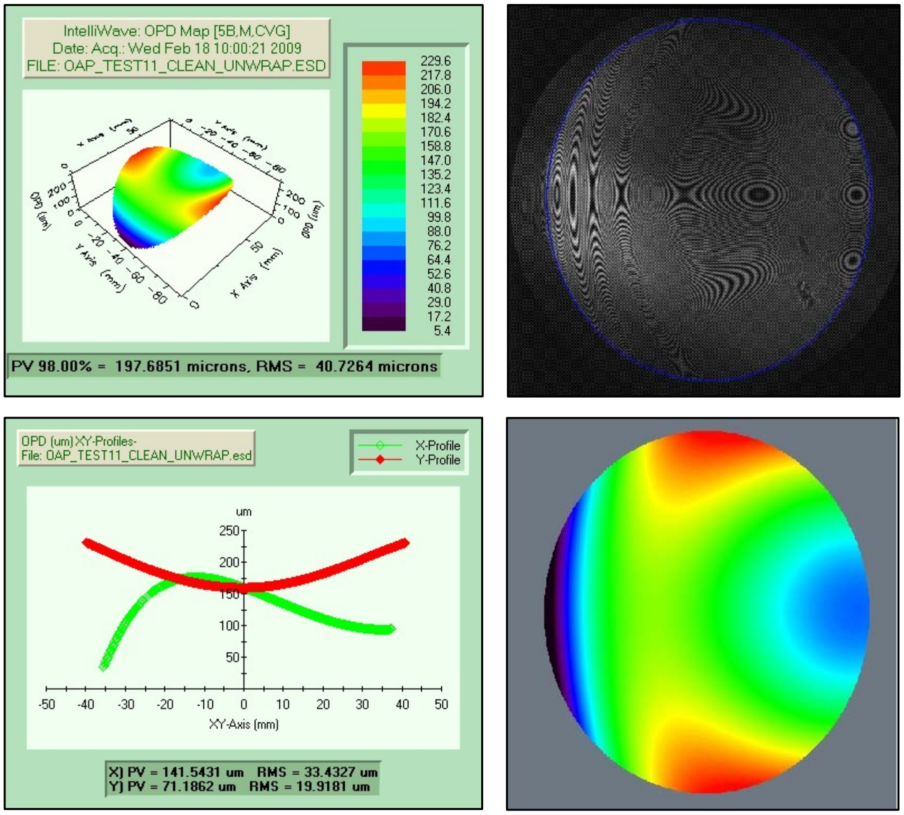


Figure 8E: Off-Axis asphere without **CGR™** subtracted

Summary

With the ***Intellium™ Asphere*** interferometer and ***IntelliWave™*** Software, aspheric measurement can be performed quickly and as easily as for standard spherical optics. Thousands of fringes can be processed by Sub-Nyquist technology and non-common path interferometer calibration is performed using ESDI's **CGR™** technology. All standard Fizeau accessories can be used. The result is a highly compact robust interferometer that literally measurers aspheres of virtually any kind in a matter seconds.

References

Computer Generated Reference™ (CGR™) technology (patent pending) was solely developed by Engineering Synthesis Design, Inc. However, Sub-Nyquist interferometry and retrace error methods were developed by references below:

1) John E. Greivenkamp, "Sub-Nyquist interferometry", Applied Optics Vol. 26, No. 24 p. 5245