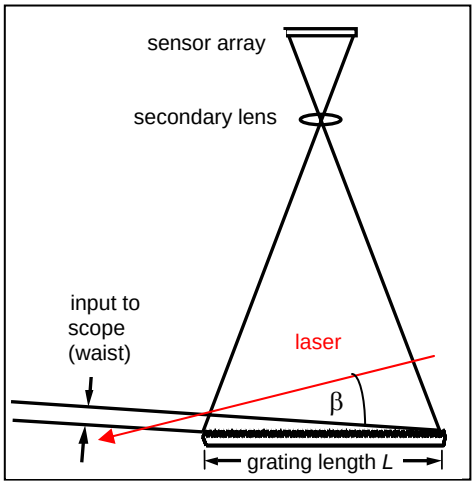
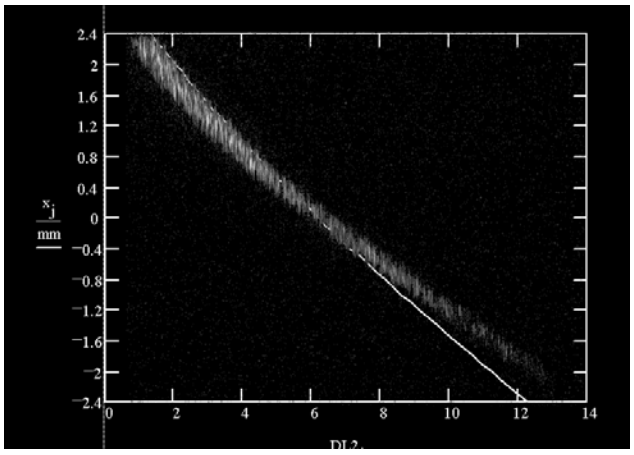
1. Results of the Phase I Project

Range finding by diffraction is a new method for acquiring distance readings which employs a diffraction grating as the primary objective in an optical system. Prior to Phase I we had already shown that in the special case where the primary objective grating has a variable pitch, such as a hologram of a point source, spatial displacements of the higher-order diffraction images can exhibit an anamorphic magnification feature. We proposed a microscope where a laser beam penetrates a narrow waist at occlusion liability angle β and intercepts targets then reconstructed across the entire grating length *L*.

In Phase I we studied by experiment whether the anamorphic magnification feature we predicted in theory was extensible to angles of grazing incidence above 80º where the magnification feature grows exponentially.

To achieve the effect, we commissioned a custom surface relief holographic optical element (HOE) from New Light Industries (NLI). The HOE was fabricated in Shipley photo resist exposed to a 441 nm laser. It was made with a reference plane wave incident on the plate at 43.5º. Such a plate will achieve 82º playback under 635 nm illumination. The object beam was a point source 295 mm directly above the plate, and the resulting HOE has a 200 mm focal length when used at 635 nm.



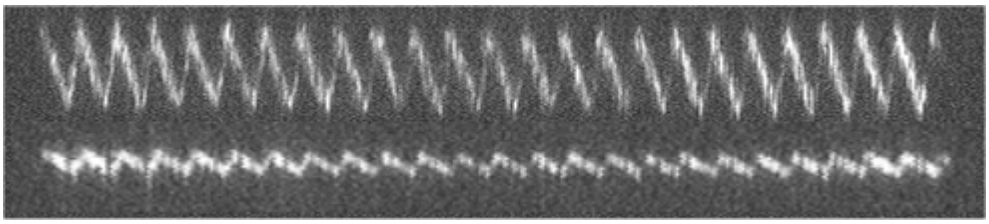


Prediction vs. Performance over 1 cm

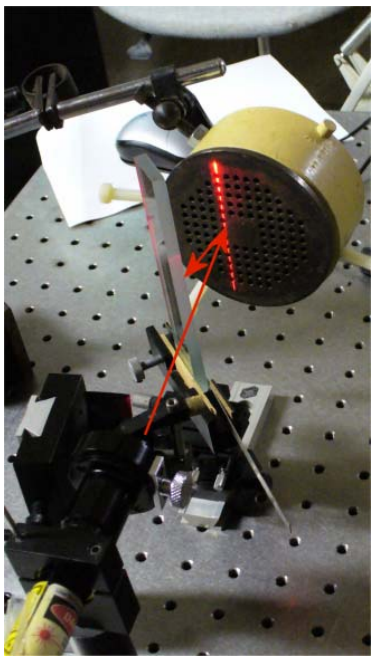
The desired magnification feature predicted by our equations was seen. It exhibited a pseudoscopic magnification in the far-field. Using our equations we found that a non-linearity can be modeled at the *extrema* by considering the step down from the recording wavelength to the playback wavelength. We graph this phenomenon in Figs 13 & 14 of our Phase I *Final Report*. Our holographic primary objective was figured to work inside the linear region.

The efficiency of the first grating was very low in the native photo resist, 1.2% at 82º grazing incidence, so the hologram was gold plated in sputtering coater to increase its reflectivity. This doubled the efficiency to 2.2%. Since, this was not enough efficiency for us to image our test patterns with eye safe lasers; we went back to our subcontractor, NLI, for a series of exposure tests which demonstrated that they could achieve 17.9% efficiency at 82º. With the optimum exposure time known, NLI made additional gratings.

We have now successfully imaged a 75 mm wide dark black metal target with an eye safe laser stripe. The desired magnification feature is clearly visible in the 1/8th inch step block. It was imaged under laser stripe illumination where the occlusion liability β between incident angle and receiving angle is 30º.

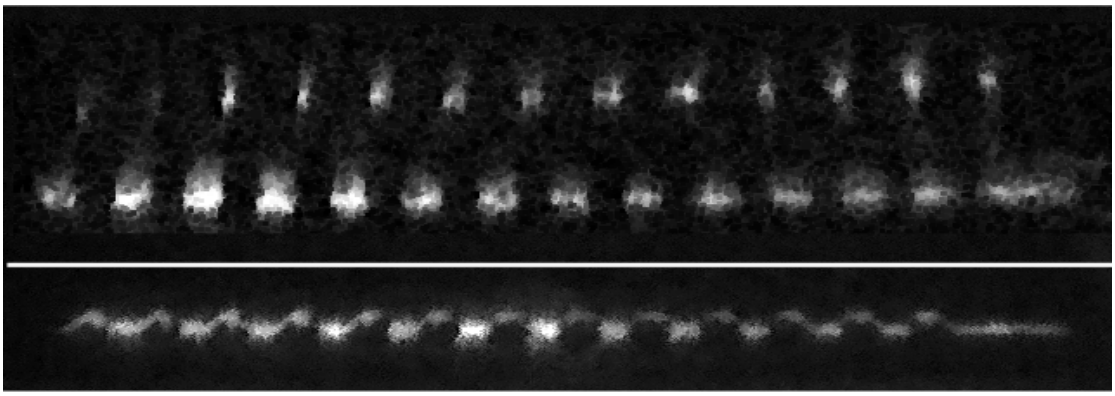


Diffraction (above) vs. triangulation (below) at identical occlusion liability angle of 30 º
The object is a machinist's work piece holder with 1/8th inch steps and a black metallic finish.



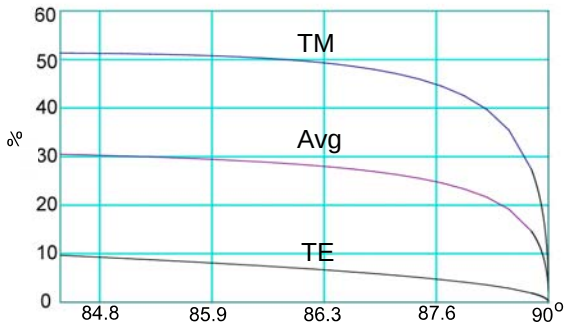
Using the same HOE, we sighted through dark metal bore holes of a type of spinneret expected to play a role in Phase II and Phase III. In the bench set up shown to the left, we compared the performance of both diffraction and triangulation when optically penetrating 3.3 mm diameter spinneret capillaries that are 17.6 mm deep. To achieve penetration from the input base to the output nozzle without shadowing artifacts, we are restricted to a 10º occlusion liability angle, β. A 5 fold improvement in displacement between our holographic profile and a conventional triangulation profile is demonstrated in the comparison below.

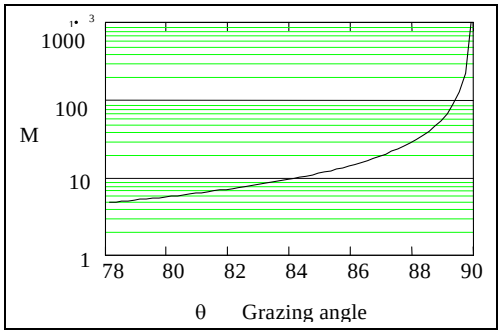
The "y to z" ratio, that is, width to depth ratio, is an important metric when comparing methods of 3D inspection. Our primary objective HOE microscope magnifies only in the depth dimension. As a result, the width of the profile can be matched to a wide target while achieving microscopic resolution in depth. Triangulation range finders also can take wide profiles, but they do not magnify. Since the resolution of both profilometers is determined by length of the deflection in the range dimension, the leverage of the anamorphic magnification feature of the HOE gives it an advantage in resolution over triangulation. Traditional refraction objective microscopes magnify by narrowing the field-of-view in both dimensions. They have short profiles and hence low y to z ratios.



Comparison of magnification by diffraction (above) vs. triangulation (below) at a common occlusion liability angle β of 10º for the example spinneret. It has 13 capillaries in a row

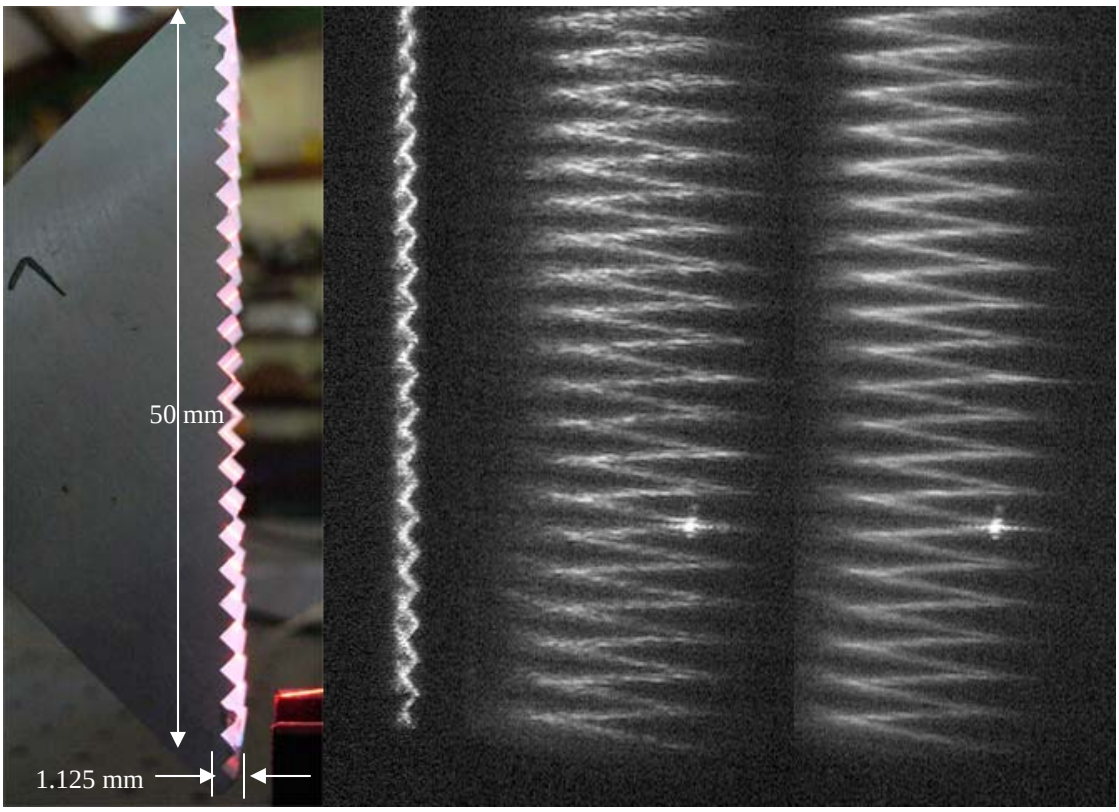
There is a trade-off between the angle of grazing incidence and grating efficiency. Using PCGrate software we have seen that as grazing incidence approaches 90º, the efficiency drops to zero. (The graph below is not for the microscope *per se* but is typical. Grazing incidence output is polarized, as indicated). Conversely as the grazing angle increases toward 90º, the magnification, *M*, increases exponentially.





Efficiency (left) compared with magnification (right). As magnification grows, efficiency decreases.

When white metal is used as the test target, more flux is available and the allowable grazing angle can grow within the linear region. The magnification is then raised. An experiment illustrates the benefit. The same HOE used for black metal was used again with a test block milled in shiny aluminum. A step block with increments of 2.5 mm and groove depth of 1.25 mm was imaged over 50 mm. Compared with the black metal experiment, magnification increases to a 10 fold profile improvement over triangulation.



Aluminum test block, triangulation profile, HOE primary objective profiles, (**speckle reduction on right**) $\beta = 38^{o}$, grazing incidence 82º, illumination Class I eye-safe 635 nm diode laser, frame time 33 msec.

Laser speckle can be reduced optically with a very small lateral translation over one frame time of integration. A translation spanning a few multiples of the illumination wavelength will blur speckle. The method works, because our HOE magnification is anamorphic. Equivalent translations in a refraction microscope will blur the target, because translations are magnified in both dimensions. A triangulation profile can exploit this method, but the profile is not magnified, and speckle is less of an issue.

There is a limit to magnification in optical microscopy referred to as the diffraction limit. The angle and wave length of a wave front striking a grating limits resolving power. We posited a theory for resolving power in our SBIR Phase I application. The theory is based on a half wave separation analysis similar to the Raleigh criterion used in spectroscopy. Details were published in an SPIE conference paper with prepublication on our web page. [*] Our Phase I *Final Report* detailed an empirical resolving power study which demonstrated that at a stand-off to target suitable for industrial inspection, 7 mm, we can resolve 10 microns over 1 cm of measured depth. This documented resolution is within an order of magnitude of our prediction, a theoretical limit of 2 microns over 1 cm.

We expect to come closer to the theoretical resolution with the addition of a secondary cylinder lens. The additional lens overcomes endemic astigmatism caused by the anamorphic magnification of the primary objective. We show a Zemax model of the improvement in the Phase I *Final Report*, p. 10, Fig 15.

[*] Thomas D. Ditto, "Three-dimensional microscopy using a diffraction grating primary objective," SPIE Vol. 5578, pp. 167-178 (2004) See: http://home.earthlink.net/~scan3d/acrobat/3D_Microscopy.pdf p. 6 *ff*

In Phase II we will address the issues raised in Phase I. We will remove speckle by opto-mechanical means when we will have a motorized motion platform holding the specimen. We also look forward during Phase II to improving the laser stripe projector using a type of laser that has temperature stabilization, since our method is sensitive to sub-micron variations in laser wavelength. We used electron microscopy in Phase I to study grating grooves, but we learned that electrostatic charge on the glass substrate interfered with metrology. In Phase II we will have sacrificial samples so we can get profile micrographs essential to efficiency optimization. As we have shown in our experiment above, efficiency will limit magnification. We will install subtle refinements to the secondary optics to remove astigmatism.

1.1 How Our Invention Compares with Prior Art

There are competing 3D optical microscope methods, notably confocal and interferometric, but the most common 3D industrial inspection systems use triangulation. Triangulation offers rapid inspection throughput for industrial production lines when applied to *macroscopic* 3D. However, triangulation does not magnify depth. In fact, it minifies the depth dimension for occlusion liability angles of β less than 90º. In practice, the value of β must be much less than that - less than 45º, because the interrogating laser will be unavoidably blocked by protruding surface features that interrupt the structured illumination beam. To overcome its limit on depth resolution, triangulation systems are sometimes coupled with lens microscopy. In this combination, triangulation systems can see microscopic features, but there are trade-offs. The field-of-view and depth-of-focus are both compromised. Speckle sensitivity is greatly raised. Triangulation 3D microscopes use expensive refraction primary objectives with short stand-offs to targets. As a result the inspection stations using microscopes are generally kept off production lines and in protected enclosures.

Stereoscopy is a variant of triangulation that is commonplace in the industrial environment when a human does the inspection. Stereo instruments have reticules for lateral measurements in (*x*,*y*), but there are no equivalent reticules for measuring 3D distances, *z*. Computers software may yet be developed to apply stereoscopy to 3D machine vision, but ambiguities in surface textures weaken all software mapping algorithms. Moreover, when dual lens systems are at a stand-off sufficient to generate stereo views, the diffraction limit lowers the microscope's resolving power below the theoretical limit of a single lens.

Confocal 3D microscopy dominates medical and biological markets, but these research instruments are not ready for industrial inspection. Throughput is limited by the millimeter scale of the visible lateral dimensions. The confocal principle does not lend itself to large scale objects in any of the three dimensions. Confocal microscopy is based on a narrow depth-of-focus, so stand-off to target is generally minimized to improve resolution. As a result, there is a danger to expensive primary objective components at a minimized stand-off. The stand-off problem is worse for confocal than with triangulation 3D as coupled with refraction microscopy, and confocal optics are more complex and costly.

Interferometric microscopes are also costly, but they can work at any stand-off while simultaneously resolving sub wavelength 3D features. One drawback to the interferometer in industrial settings is the requirement that the target and microscope be held to a level of stability equivalent to a fraction of the wavelength of the illumination. This demand for stability prohibits use of interferometric microscopes on industrial production lines. Also, an interferometer does not give absolute range measurements. The measured interference pattern is a relative displacement over the excursion of the illumination wavelength. Ambiguities caused by discontinuities can be removed over many sequential exposures, but the processing penalty along with the increased complexity in the mechanical stages becomes a significant expense.

Our microscope uses a novel technique. It has immediate applications in industrial inspection that prior art cannot address economically. In the long run, it may compete in general scientific venues.

3D Inspection Method	Resolution	Stand-off to target	y:z ratio	Depth of Focus	M'scope objective	Production Line
HOE Primary	5 microns	1 cm	50:1	2 cm	$10	Yes
Triangulation	500 microns	10 cm	1:2	5 cm	$0	Yes
Tri. + Microscope	1 micron	1 mm	1:2	1 mm	$1,000	Some
Confocal	500 nm	10 microns	1:1	1 mm	$2,000	Not Yet
Interferometer	100 nm	10 cm	1000:1	1 cm	$4,000	No

2.