Wavelength compensation at 1.064μ using hybrid optics

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ABSTRACT

The wavelength scaling of an f# 2.5 off axis HOE from 488 nm to 1064 nm has been done. We canceled large induced astigmatism, and other higher order aberrations using a combination of 1 curved reflector, 1 cylindrical lens and one Null CGH bonded to the cylindrical lens. The task was made more difficult by a requirement to fill a 404 mm round aperture and make it focus to a 53 micron diameter spot at the 1/e clip level. The design procedure, the construction sequence and the measured results are presented as a work in progress.

INTRODUCTION

Our primary objective is to design and construct a 45 degree off axis f#2.5 Lidar scanning optic for operation at 1.064μ. The focal length was selected at 1016 mm with the focus centered and normal to a 404 mm diameter glass sandwich, and the input was designated to enter from 45 degrees off axis so that conical scans of the sky could be made. We had previously tried to obtain a 500 micron spot with an f# 4 design at 670 nm and had succeeded nominally using only a tilted 60 mm fl parabolic mirror and two positive cylindrical lenses[1] to correct the astigmatism and some of the coma like aberration. We also made a design that predicted better performance using a large, tilted and decentered medium power positive meniscus lens, a tilted negative cylinder and a 446 mm D by 1994 mm fl telescope mirror. The design looked good enough to try and we converted to 1.064μ, re-optimized and made a prototype. The spot became nominally smaller, about 400μ but not the 250μ that the design predicted, probably because alignment errors were accumulating.

We then added two weaker meniscus lenses on axis to reduce spherical and replaced the large tilted medium power meniscus with a smaller but much stronger positive meniscus to further reduce coma. The predicted spot was to be 200μ plus whatever the random phase error in the glass substrate might add. The computer model was not faithfully translated to actual optics and we had considerable residual astigmatism and other aberrations left over. We measured narrow areas in the lines down to 200 microns and decided the set-up had to be simpler and the design had to reduce the aberrations to a few waves, not the hundred or more waves we had been getting.

DESIGN CHANGES

Conventional spherical optics.

The last two conventional optics designs I actually tried and tested were nightmares 1064B and 1064F, the layouts are shown in figure 1 with some thru focus diagrams. The apertures of the optics prevented making a full aperture HOE. Figure 2. is the test layout at 1.064μ which also shows the way the HOE is supposed to work and some of the best measured "spots" are shown.

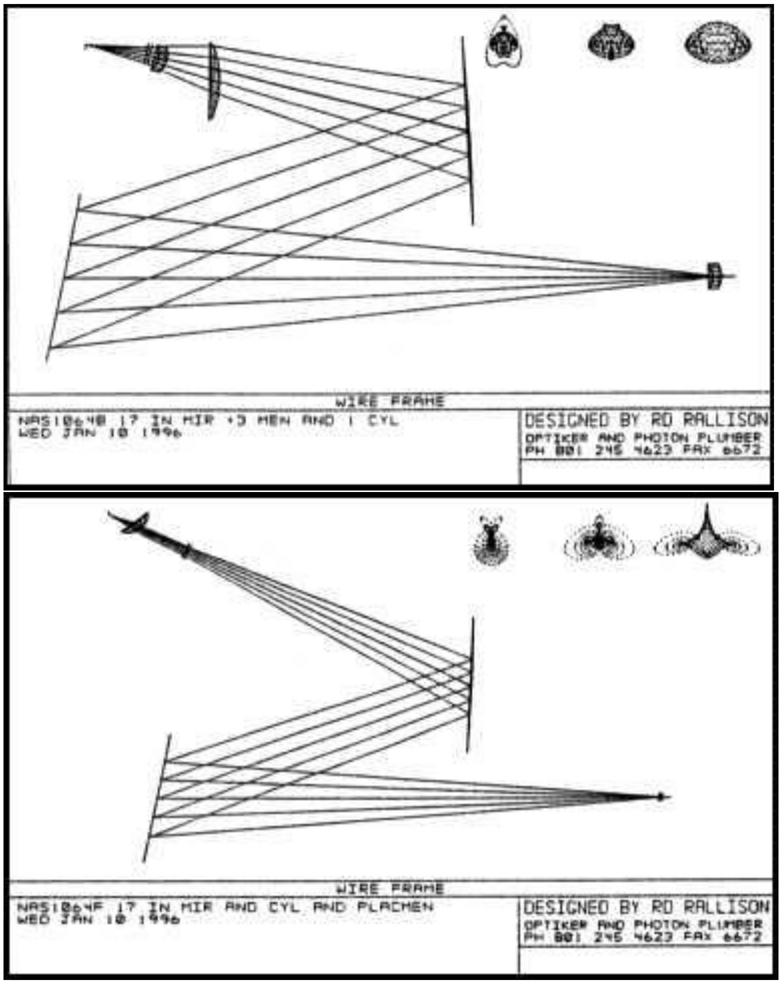
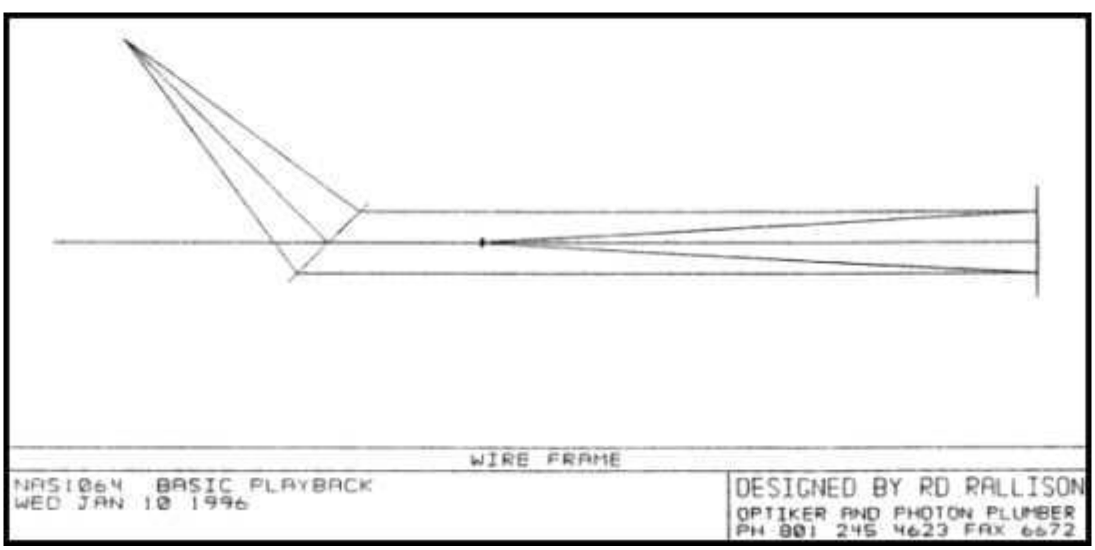


Figure 1. Construction layouts using only available conventional optics and traced spots of about 150μ.



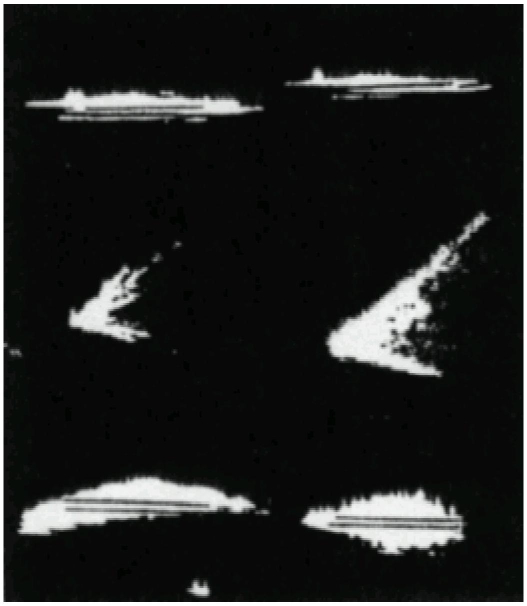


Figure 2. The test set up used to measure the reconstructed point at 1.064µ and some measured spots. The space between dark parallel lines is 63 microns. Astigmatism dominates.

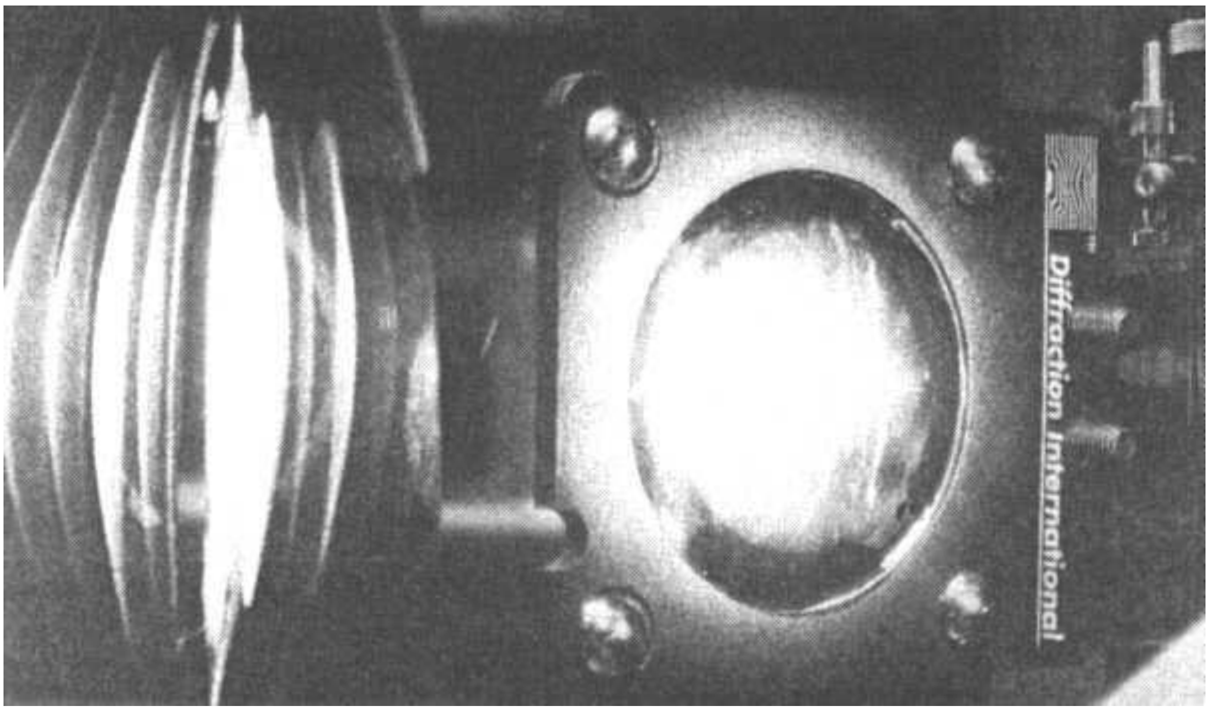
These designs began to look like dead ends, as the number of elements increased, the number of possible configurations ballooned and optimization became far from obvious. It was clear that a custom made surface was the only practical solution, the two choices were a potato chip chunk of glass or a binary phase HOE. We had a lot more experience with phase HOEs so I asked Steve Arnold for help.

Hybrid refractive / diffractive surfaces

Steve suggested we zero out the phase error with one of his CGH nulls[2] placed on the flat side of a cylindrical lens, creating a hybrid optic. If the CGH were made into a binary phase structure we could have as much as 40% in the desired order. I imagine that the alternative would have been to shape a surface into something like a Pringles potato chip and attach it to the lens. Steve took my Zemax generated design and plugged in the appropriate numbers to his super Oslo program and went to work. There was a bit of luck going for us. The telescope mirror could be moved just a little and be made to form a line focus a comfortable distance from the cylinder, enabling us to mask out unwanted orders from the binary optic. He also found that the exit light from the lens was about 35 mm in diameter and fairly uniform, the size and uniformity was favorable for fabrication of the binary CGH and for playing it back through the system at 488 nm. The number of waves of correction was also manageable at about 160.

The optimization in Oslo, subsequent chrome mask generation[3] and phase element fabrication went smoothly, the final assembly traced out to yield about 1 wave of higher order aberration. I also took a crack at designing the CGH in Zemax but I was only able to optimize to about 4 waves (20µ spots), obviously I still have something to learn. I was much more successful at converting a chrome mask version of his Oslo design into a high efficiency volume phase HOE. Simple contact copies into DuPont photopolymer[4] yielded 30% in the 1st order, copies into UV glues diffracted up to 14%, dichromate gelatin in 25µ thicknesses grabbed 26% and unbleached silver grain films diffracted about 4% to 6%. The original chrome mask was not measured. The dichromate copies had the best optical properties.

The phase only CGH from Steve, made on photoresist, measured about 18% efficiency at 488 nm and was clean and scratch free until I started using it. At this point I have done so much damage to it I will probably have to get a new cylindrical lens and bond a DCG copy of the chrome mask to it and begin again, in order to get the best possible recording. The original assembly mated fused silica to a flint glass lens, which gives rise to an interference pattern in the object beam that could be reduced by recording the DCG copy on a flint substrate, and damage in use can be minimized by capping the DCG with a thin AR coated cap of flat 7059 glass. A photo of the Hybrid optic is shown in figure 3 below, alongside of a scaled image of the pattern minus the carrier we added to it. There are 20 waves of error per fringe.



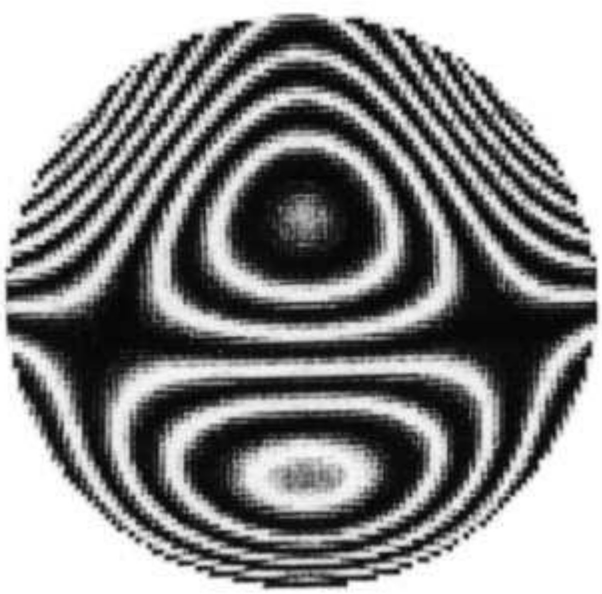


Figure 3. The hybrid optic from Diffraction International and the CGH pattern without carrier.

Modeling in Zemax and in Oslo

I made an attempt to model the Oslo diffractive design in zaman using the following conversion formula but I could not make it work properly. Those who are familiar with Oslo or zemax will recognize some of the terms. The As are the possible 65 polynomial coefficients optimized in Oslo, the Bs are the corresponding coefficients in the zemax binary 1 surface. The j+k is the sum of the powers of x and y and the quantity in brackets is a phase in waves, unique to Oslo or at least not chosen in zemax.

$$B_i = \rho^{(j+k)} \left[\frac{2\pi M}{\lambda_r}\right] A_i, \text{ where } \rho = 100 \text{ if mm are chosen lens units.]}$$

We need the conversion so that either model can be rearranged to accommodate another exposure geometry for this work in progress. At least 5 other designs have to be worked out and fabricated before we are done with this project. At least one of them could use the same CGH. Another improvement to the model would be an accurate representation of the B270 sheet glass substrates we are working on. The sheets appear to be consistently flat within a few waves in one direction and rippled a few more waves in the other direction, one side is usually flatter than the other, which will not matter since we are bonding two plates together with flat sides turned outward and rippled sides index matched together.

The figure below shows the final recording geometry using the Hybrid optic with the diffractive part bonded to the flat backside of the refractive part. All parts were initially positioned within 1 or 2 mm of the optimized position and all angles were within about 3 mrad. Sadly, that was not close enough to produce the desired results and many adjustments have been made during trial fabrications. A three axis mount was used to position the hybrid but the parabolic mirror gave us most of the alignment trouble.

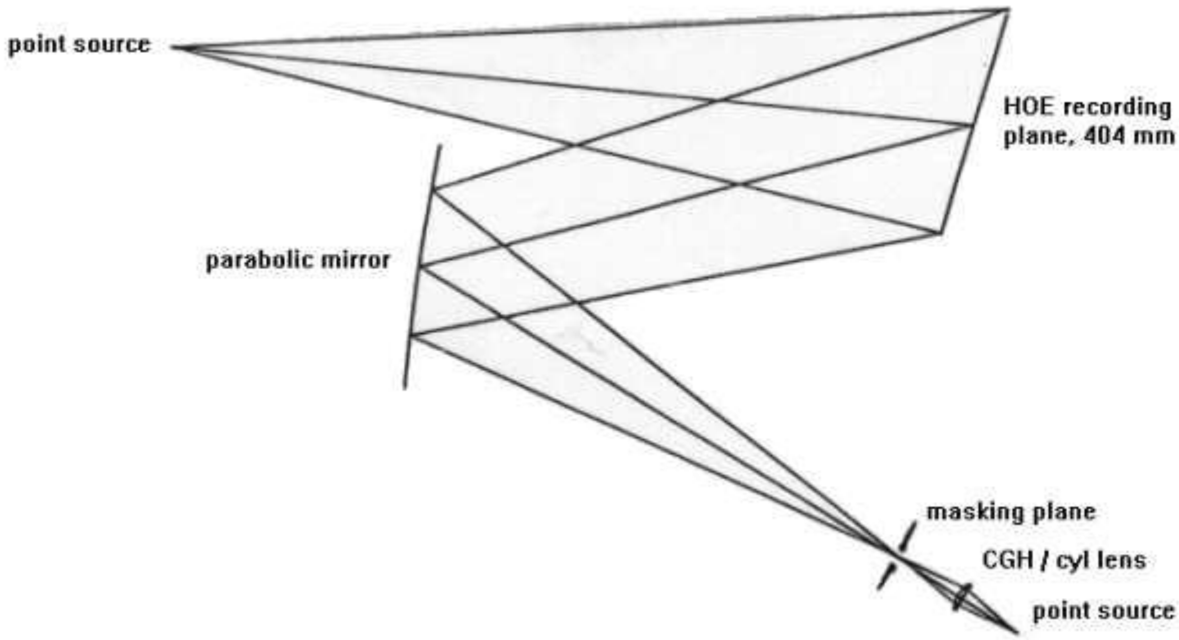
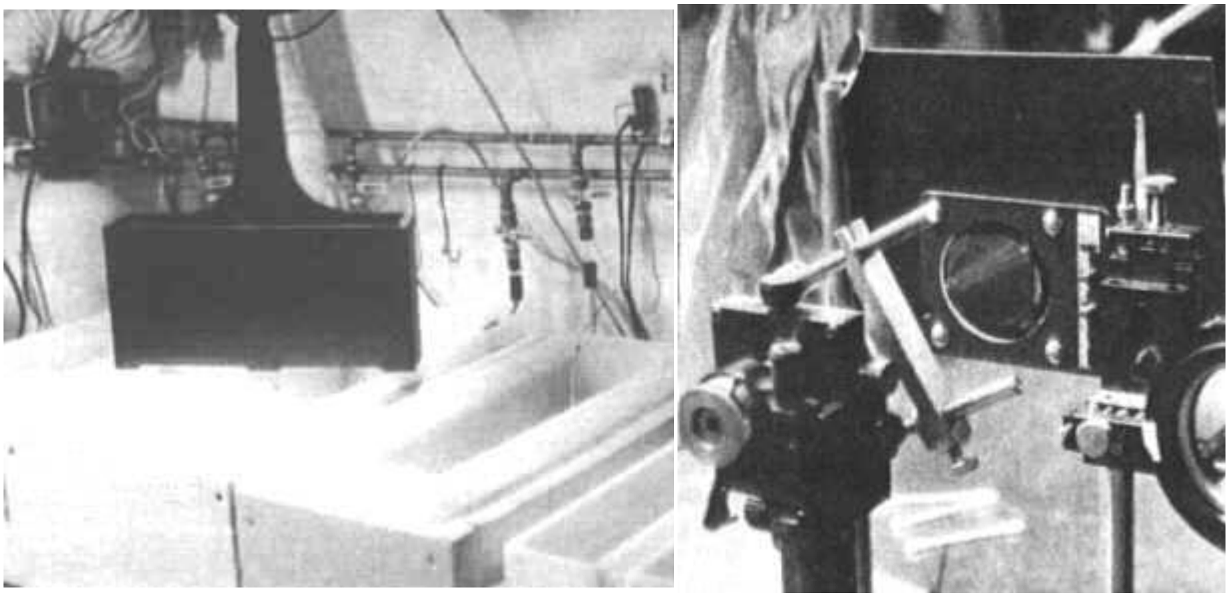


Figure 4. The final layout design using the Hybrid optic.

CONSTRUCTION OF HOE

The coated plates are our own spun on dichromate gelatin[5] (DCG) with 30 percent dichromate in a 7 - 8 micron layer of Grayslake gelatin. We age it at room temp for 2 or 3 days prior to exposure so that it will harden and reconstruct with maximum clarity. Most plates are clean and uniform and otherwise consistent and reproducible. The exposures so far were made with about 600 mwatt of 488 nm light from an argon laser and the required energy is 10 mJ/cm*cm for masters and 40 mJ/cm*cm for infrared copies. Processing is in standard IPA and water preceded by a 2 minute soak in Kodak fixer. The plates are typically cycled through each bath in 30 seconds with continuous agitation and are reprocessed as needed to get peak diffraction efficiency at 1.064µ or for masters adjusted to 50% @ 488 nm. An entirely new processing station was constructed for this project. About 50 gallons of IPA is now heated to 55 deg C with circulating hot water. The water is pumped through a remote gas water heater and stainless steel tubing looped in the bottom of each of three processing tanks, enabling economical and safe operation. Figure 5 below shows the process station and optics with mounts used during exposure.

In this work we exposed 406 mm square (16 in) B270 plates with exposure times of from 4 to 16 minutes. The chance that something will warp or bend or that the laser will drift during that time is about 10:1. An electronic fringe locker was used to be certain that at least one portion of the HOE would always turn out perfectly. When all due precautions had been taken and extended settling times provided for, the results were good. All of the goals for this project have not yet been met. We will yet have to produce a contact copy from a master using anodizing techniques to get a uniform response over the entire aperture. The contact copies can also be made to meet the Bragg condition more uniformly because the angle the copy light travels in has only a small effect on the diffraction pattern but a large effect on the tilt of the Bragg planes. The best possible copy beam at 488 nm will be an astigmatic wave, produced by placing an appropriate cylindrical lens some distance in front of a pinhole. This work has yet to be done.



3 hot IPA and 2 cool Water and 1 Fix tank

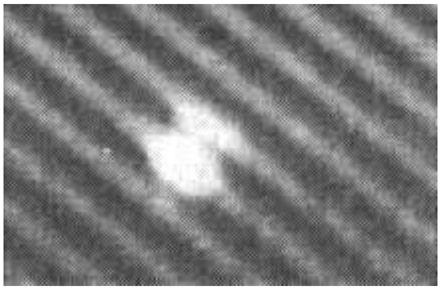
Optics used to form Object wave

Figure 5. The 406 mm (16 inch) processing station and the hybrid optic with associated mounted optics.

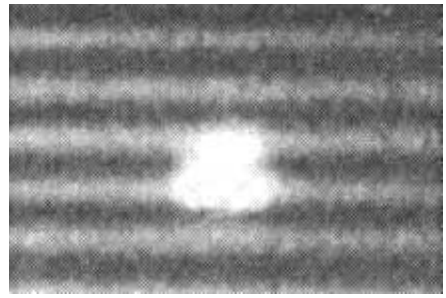
Figure 5. The 406 mm (16 inch) processing station and the hybrid optic with associated mounted optics.

EXPERIMENTAL RESULTS

As of this writing we have achieved a slightly astigmatic spot that measures only 60µ in the direction of diffraction at the 1/e clip level and is about 70µ at the other best focus, a mm in front of the best spot. Measurements were made with a Beams can rotating slit from Photon Inc. Spot profiles were also viewed on a screen that attached to a Rhonchi rule with 63µ open spaces. The first two spots shown below in figure 6 belong to plate # 8 and meet our criteria, except for that tiny mm of astigmatism. These spots were found in a HOE that was misaligned somewhat in the Z direction, which made me suspect that one of the powered components was not made as modeled. We had modeled the mirror assuming it had a 1994 mm (78.5 inch) focal length and it is really 1999 mm (78.7 inches). I have another mirror that is 1996 mm (78.6 inch) fl and have since substituted it and moved it back slightly to account for the change. It was then that I discovered just how sensitive the system was to a tiny tilt error around the Y axis. Spots 3 and 4 from plate #13 were the result of less than .05 degree error in the tilt of the telescope mirror. Spots 5 and 6 from plate #15 are the result of translating the hybrid optic in the x direction 2 mm and tilting the mirror .5 degrees about y. Moving the hybrid optic 2 mm along the Z axis only doubles the spot size. We are going for as near to zero aberrations as we can practically get and are continuing to fine tune the set up to eliminate as many measurable flaws as possible. Unfortunately the current set up is not yet producing spots as small as the previous set up and fine tuning with big plates is extremely time consuming, nevertheless we now expect to get 60 micron spots in a finished product.</block quote>



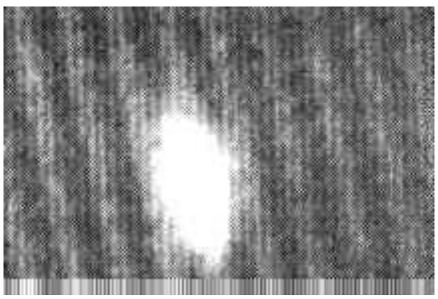
(best place to date)



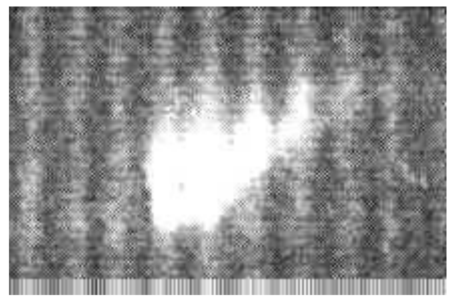
#1, far focus 1016 mm

plate #8

#2, near focus 1015 mm



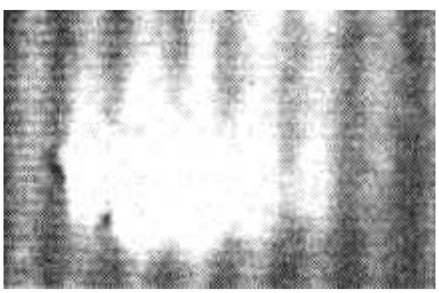
(close second best)



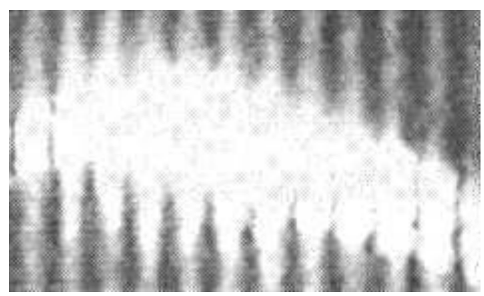
#3, far focus 1017 mm

plate #13

#4, near focus 1013 mm



(result of changing mirror)



#5, far focus 1016 mm

plate #15

#6, near focus 1008

Figure 6. Three sets of measured through focus spots, from 3 recent

plates. Plate #8 had only 1 mm between spots, # 13 had 4 mm between and #15 had 8 mm. The space between dark bands is 63µ.

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zemax conversion was provided by Ken Moore, author of zemax.

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Secondary HOE

Another way to ruggedize the system and get more light in the diffracted order is to record the diffracted wavefront with a 30 degree off axis point source reference in 8 of DCG. A convenient plane to record this secondary HOE is found about 200 mm from the mask plane where the pattern is uniform and fits nicely on a 200 mm square plate. The secondary HOE replaces the Hybrid HOE in all subsequent recordings and makes exposures shorter and more likely to succeed. Alignment errors could be worse.

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WAVELENGTH COMPENSATION AT 1.064

MICRONS USING HYBRID OPTICS

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Holographic Optics designed for use in the near IR region cannot usually be made with near IR lasers. Common recording media is naturally more sensitive to higher energy visible (blue) wavelengths. The large wavelength shift produces large aberrations. We previously made off axis focusing HOEs for 1.064 microns with blue light at 488 nm with refractive and reflective optics to reduce aberrations. We recently had success nearly nulling out those aberrations by adding a general diffractive surface to one of the refractive optics. We have reduced the errors in the IR wave fronts to a few waves over a 404 mm aperture using only off the shelf optics and a custom CGH. The method results in complete construction geometries being generated ready for implementation on a table. The general method used is time reverse ray tracing of the refracted and diffracted construction wave fronts. A 2 degree carrier is added to the phase map to separate and block unwanted diffraction orders. A binary phase HOE is then generated to diffract 35% or more of the 488 nm light into the construction path. Super OSLO and Zemax optical design programs are used to design the construction optics.