Digital Holography using a Laser Pointer and Consumer Digital Camera

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Available online at http://pegasus.me.jhu.edu/~lefd/shc/LPholo/lphindex.htm

Acknowledgements

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Project idea and direction: Dr. Edwin Malkiel, malkiel@titan.me.jhu.edu

Digital holography reconstruction: Jian Sheng, jiansh@titan.me.jhu.edu

Abstract

The point of this project was to examine the feasibility of low-cost holography. Can viable holograms be recorded using an ordinary diode laser pointer and a consumer digital camera? How much does it cost? What are the major difficulties?

I set up an in-line holographic system and recorded both still images and movies using a $600 Fujifilm Finepix S602Z digital camera and a $10 laser pointer by Lazerpro. Reconstruction of the stills shows clearly that successful holograms can be created with a low-cost optical setup. The movies did not reconstruct, due to compression and very low image resolution.

Theoretical Background

What is a hologram?

The Merriam-Webster dictionary defines a hologram as, “a three-dimensional image reproduced from a pattern of interference produced by a split coherent beam of radiation (as a laser).” Holograms can produce a three-dimensional image, but it is more helpful for our purposes to think of a hologram as a photograph that can be refocused at any depth. So while a photograph taken of two people standing far apart would have one in focus and one blurry, a hologram taken of the same scene could be reconstructed to bring either person into focus.

The advantage of holography lies mainly in small-scale applications. When you take a photograph of a room, many things are in focus (like your roommate, his desk, and the wall behind them). The depth of objects in focus is called the 'depth of field'. So in a large-scale photo the depth of field might be several meters. The depth of field is related to the smallest resolution of the image, and when the resolution becomes much smaller, the depth of field becomes even more dramatically small. So on the microscopic level the depth of field might be on the order of microns! This is where holography is at a huge advantage, because the image can be refocused at any depth ('any' depth is not truly accurate; the depth of field that can be focused is around 100 times greater).

How do you record a hologram?

{The basic components of a holographic system are the laser, lenses and camera.}

The most common method of holography is called "in-line" holography, logically because all of the components are in a line. The image you get is actually the shadow of whatever lies in your field of view, so you cannot see the color of an object using this method.

The laser light provides all of the illumination, and other lights will detract from the quality of the hologram, so all of the images in this paper were taken in a mostly-dark room.

The laser light must first be expanded and then collimated (i.e. parallel, the beam is not expanding or focusing)[**]. When the light passes through the test section, some of it hits objects and deflects, but some passes straight through. Other objects, such as dust on the lenses, will also deflect light. The combination of the direct light (this is called the Reference beam) and the deflected light hitting the recording medium creates an 'interference pattern', if the beams are *coherent*. The light that hit an object must travel further than the light that just went in a straight line. If this distance is greater than the coherence length of the laser, the two signals will be out of phase and the interference pattern will not appear.

Coherence should almost never be a problem with in-line holography because the difference between the distance traveled by the signal and reference beams is very small (< 1cm). This is why a laser pointer is sufficient to produce in-line holograms. Other types of holography, such as off-axis recording, separate the reference beam from the signal beam before the light passes through the test section. If the paths traveled by the two beams are dramatically different, coherence can be a problem.

Another reason why in-line holography is possible with a laser-pointer is the power required. Since you are only casting a shadow, the light does not have to be very bright. Other methods of holography (off-axis, back-scattering) record the light reflected from objects. This requires much more illumination!

[**] Holograms can also be created using an expanding laser beam, but the magnification will vary with depth and this must be compensated for in the reconstruction program. DigiHoloWin does not compensate for this effect so you must use a collimated beam, or write your own reconstruction program! See next section, '*How do you reconstruct a hologram?*'

The spacing of the interference pattern is the information used to reconstruct the hologram. The result is a photograph that can be refocused at different depths, rather than being in focus at only one position.

The laser light needs to cover the entire imaging area, which is why it is expanded at the start. This is also why a camera lens is not needed; you don't want to focus the light from infinity to a point, instead you want it to cover the entire recording medium.

How do you reconstruct a hologram?

{Reconstructing a hologram means to bring it into focus at a specific depth.}

I have been careful to say ‘recording medium’ thus far, meaning either film or, for a digital camera, a CCD chip. Holograms can be recorded on special semi-transparent holographic film, however the film is expensive, difficult to develop (and often dangerous because of the chemicals used!), and requires a holographic system matching the one used to record in order to reconstruct.

Digital holograms are saved as a file directly and reconstructed using a computer program. They are simpler to record and reconstruct, and astronomically cheaper, however resolution is much lower than with holographic film. You could also create holograms using a normal film camera and then a scanner to create a digital file, however from this point on I will assume a digital camera is being used.

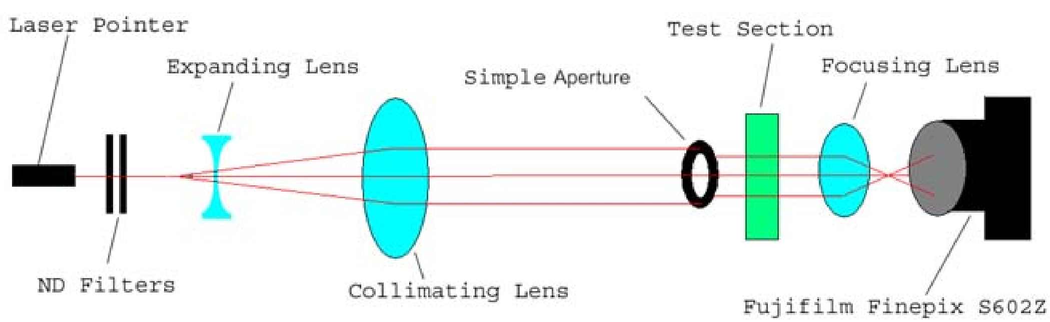
Digital reconstruction is accomplished using Fourier transforms. For more information on this, contact Jian Sheng. He wrote the program that was used to reconstruct all of the holograms in this project. It reconstructs one image at a time by calculating the appropriate filter for a given depth, wavelength of light, and resolution (microns/pixel). This filter is convolved over the entire image, generating one point per filter position, to create the reconstructed image. It currently only operates on grayscale images, so color images must first be converted using a program like Videomach[2].

You can download 'DigiHoloWin' (which includes the program as well as a Windows interface) at http://pegasus.me.jhu.edu/~lefd/shc/LPholo/DigiHoloWin.zip

Eventually we will have a help file to explain the data field entries; in the meantime you can contact us for more information. Note that this program is the property of Jian Sheng- all rights reserved. Please contact us if you plan to use it.

Experimental Setup

Components: optical rail, mounts, power supply, laser pointer, neutral density filters, lenses, test section, camera



The beam source is a $10 laser pointer by "Lazerpro". The batteries ran out on the first day so after that it was connected to a variable power supply set at 4.5v.

Wavelength = 650 +/- 10nm, Power Output < 5mW, Power Consumption = 0.3mW

The beam is first dimmed using Neutral Density (ND) filters, because initially it was over-saturating the camera. I usually used an OD (Optical Density) value of around 3.5 to get a bright image. This is a surprisingly high value, but using less would oversaturate the image in some places.

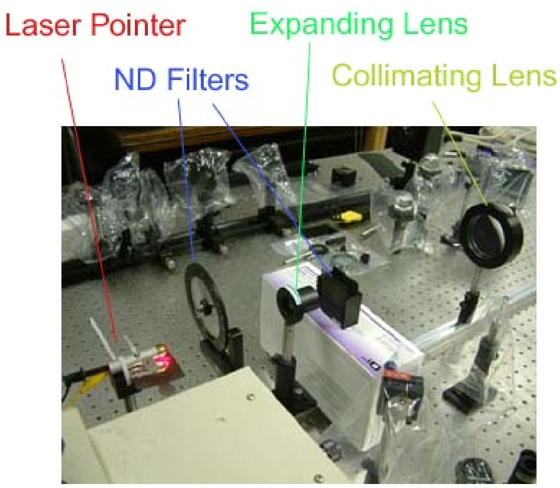
The beam is then expanded using a concave lens. This makes it look like the light is expanding from a point source located at the focal distance of this lens (closer to the laser, see diagram).

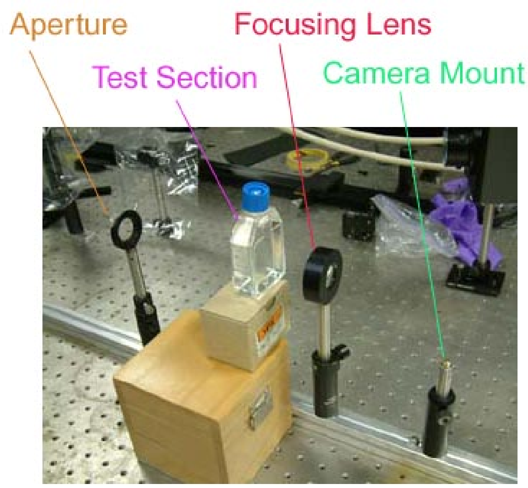
The collimating lens is placed at its own focal distance away from the point source. So the distance between the lenses is the focal length of the collimating lens minus the focal length of the expanding lens.

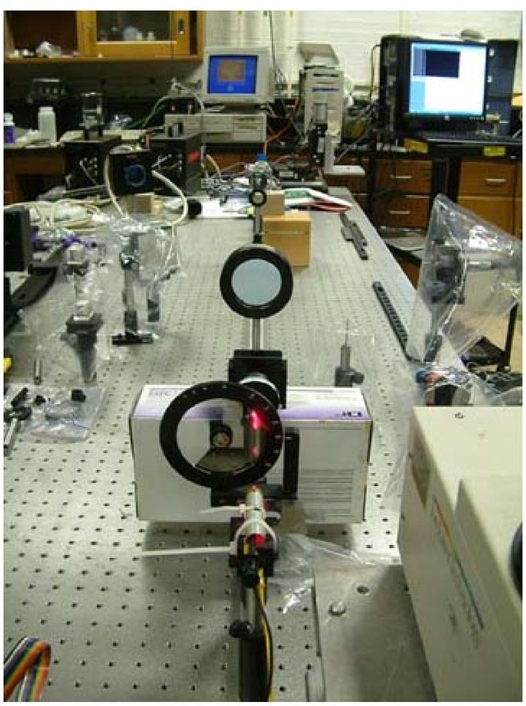
Part of the beam was weak, so I used an aperture to block some of the dim area.

The test section was a small plastic bottle with flat sides. To figure out where to place it, I moved a test pattern slowly towards the camera until it came into focus (this is the ‘zero point’ for reconstruction). Theoretically it could be placed anywhere between the collimating lens and the camera, but moving it as close as possible to the camera reduces losses.

Ideally I would have taken the lens off of the camera and just had the light impact the CCD chip directly; however since that was not possible with the Fujifilm Finepix, I added another lens directly in front to counter-act the effect of the camera lens. It was impossible to know the exact location of the chip or the lens in the camera, so this was an approximation. The lens system has an identical effect to moving the CCD chip to the 'zero point' mentioned above and adding a magnification factor (without a lens system, the zero point would be the CCD chip itself and the magnification factor would be 1). To determine the resolution (microns/pixel) and magnification I took images of a target section- see **Calibration**.


Laser Pointer
ND Filters
Expanding Lens
Collimating Lens

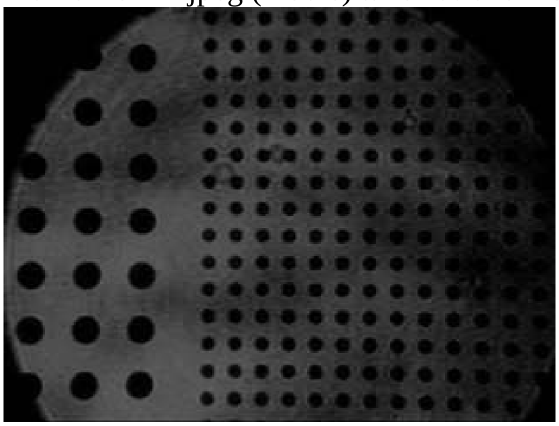

Aperture
Test Section
Focusing Lens
Camera Mount



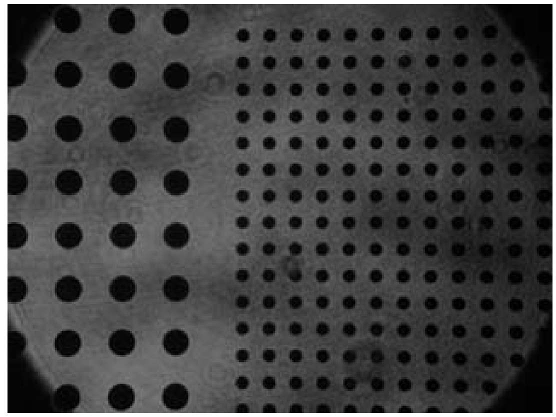
Calibration

For reconstruction, the resolution of the images (microns/pixel) must be known. It is easily determined by shooting a test section, for both movie and still capture mode:

Frame from mjpeg (movie) taken at 640x480



Tiff image (still) taken at 2832x2128



As you can see, the field of view is the same in both images, so the smaller resolution image still uses the whole CCD chip and just drops pixels (meaning the pixel spacing is much larger!).

The large circles on the test pattern have a 0.5mm diameter and 1mm spacing. The small circles on the test pattern have a 0.25mm diameter and 0.5mm spacing. By simply drawing a line on each image and counting the pixels:

The resolution of the tiff image is 3.6 microns/pixel. Recorded in grayscale.

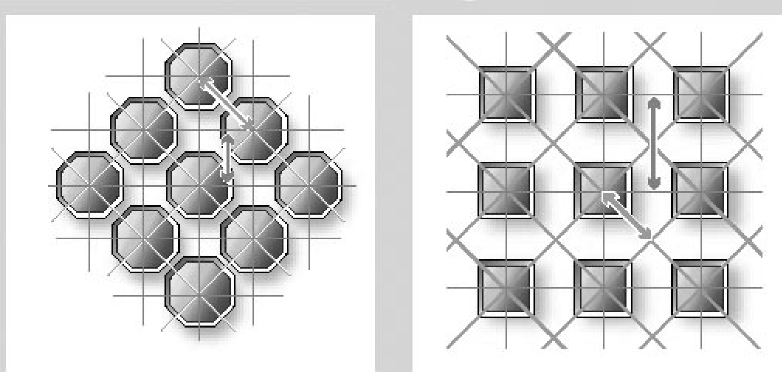
The resolution of the mjpeg image is 16 microns/pixel. Recorded in color.

Resolution is not the only factor in the quality of the hologram. The compression routine used to store an image in memory will reduce quality, and the filter used to create a color image effectively outputs only one pixel for every four on the CCD chip! The tiff format used by the Fujifilm Finepix is uncompressed[3], but all other formats are compressed. A 128Mb memory card can hold only five of the large tiff files, however.

I also determined the magnification of the optical setup based on the physical spacing of pixels on the chip, although this has no impact on the experiments.

The CCD chip for the Fujifilm Finepix S602Z is listed as '1/1.7'. This number refers to the diagonal of the chip, but is based on an extremely outdated convention[4]. I approximated the diagonal of the 1/1.7" chip by taking the diagonal of the 1" chip (which is 16mm) and dividing that by 1.7 to get 9.4mm. If you have noticed, the name of the chip ("One inch") does not correspond to any direct measurement.

The width/height ratio of the chip is 4/3, so applying the Pythagorean Theorem gives a chip size of 7.5 x 5.6 mm. The chip contains approximately 3.1 million pixels[5], which corresponds to a pixel spacing of 3.7 microns/pixel. The Fujifilm SuperCCD chip has hexagonal pixels[6], so the rows are all oriented at 45 degrees (see diagram). The camera interpolates to create a larger 6 megapixel image. This image is like having a chip with 2.7 microns/pixel spacing (only not as good!).



Super CCD
By rotating pixels 45 degrees to form an interwoven layout, the Super CCD's pixel pitch in the horizontal and vertical directions is narrower than in the diagonal direction, achieving higher horizontal and vertical resolution.

Conventional CCD
With conventional interline CCDs, pixel pitch in the diagonal direction is narrower than in the horizontal and vertical directions, resulting in higher diagonal resolution.

(see endnote 5)

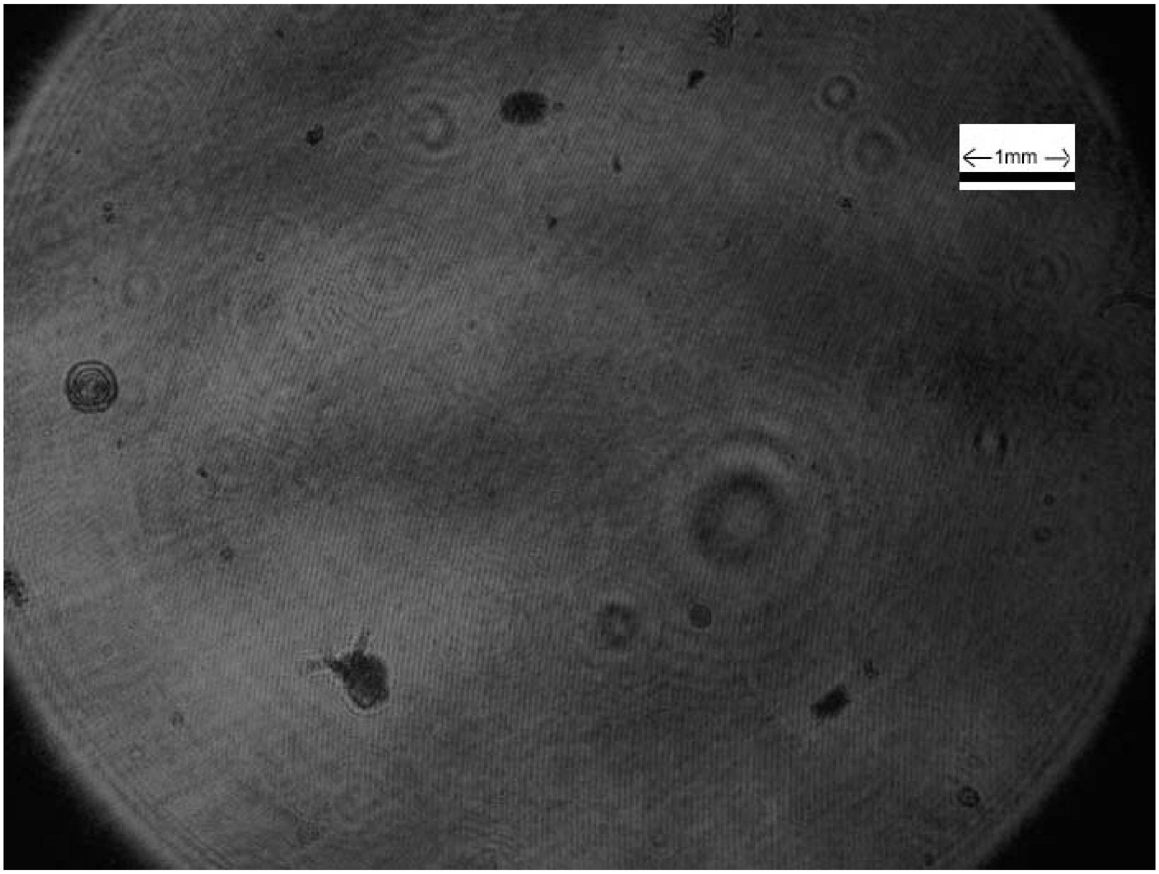
The high quality tiff images I took of the test section had a resolution of 3.6 microns/pixel, so the magnification of this optical setup was 2.7/3.6 = 0.75

Data

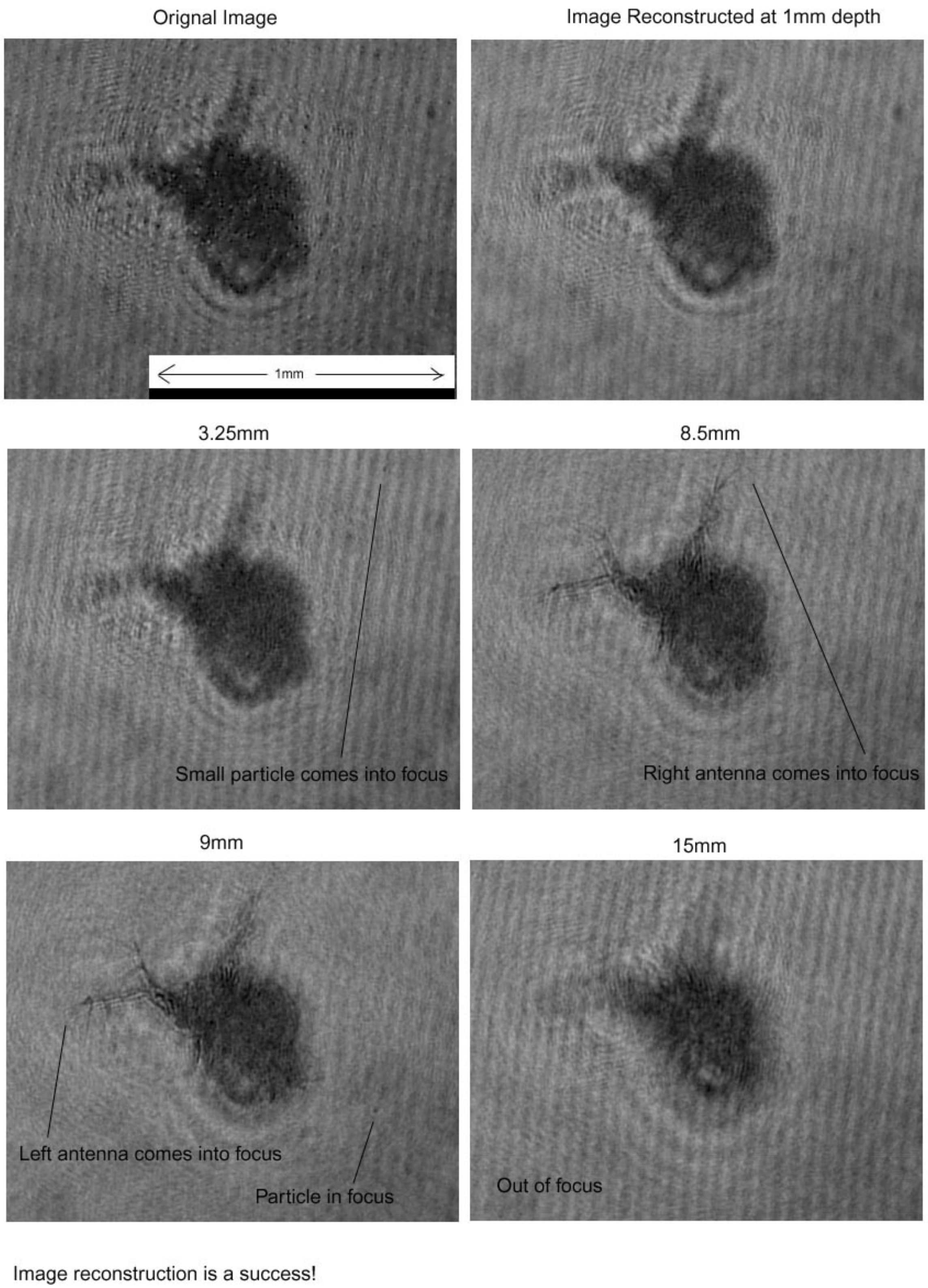
We now have the necessary information to reconstruct holograms we will record. See **Theoretical Background**, *How do you reconstruct a hologram?* for a description of the reconstruction technique. Test specimens were obtained from the Chesapeake Bay, at Fort Howard park on Sparrows Point.

Still Images

The tiff image below was recorded at a resolution of 3.6 microns/pixel (see **Calibration**)



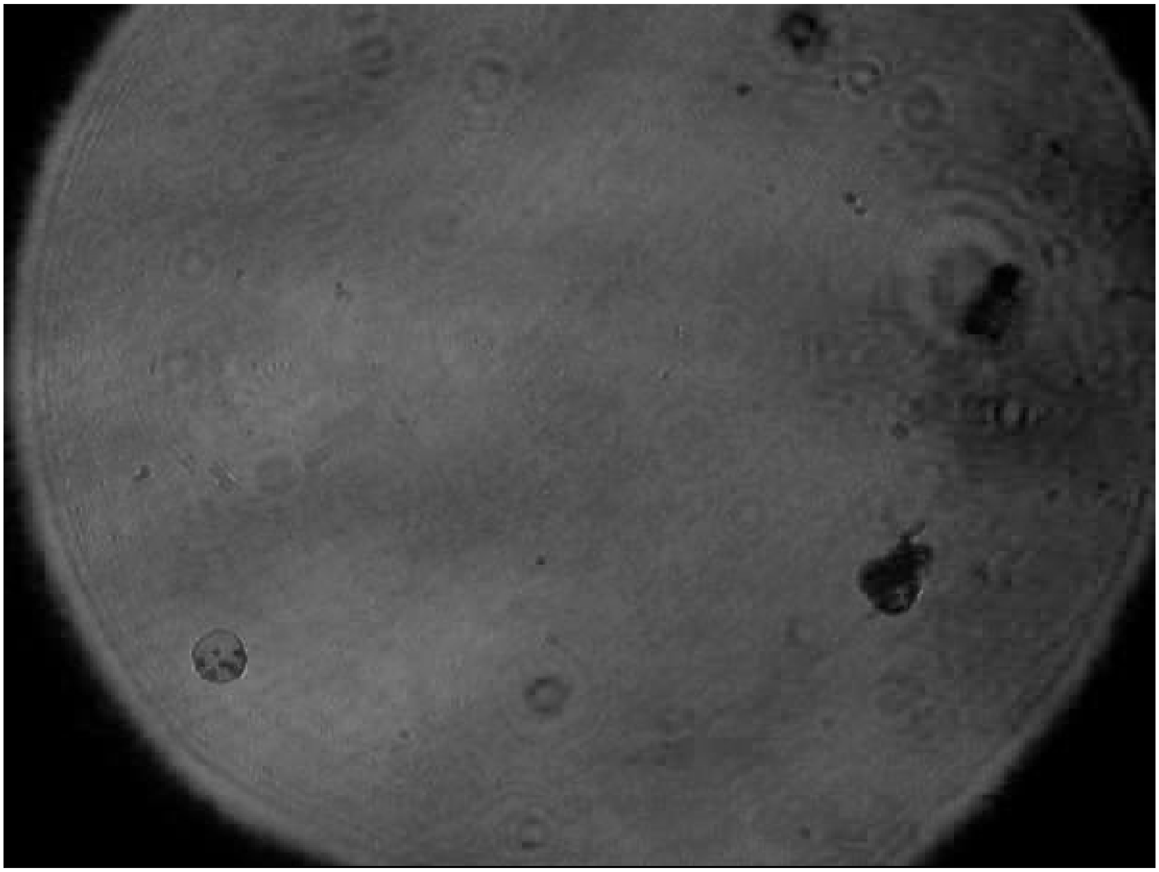
Original size is 2832x2128, Grayscale. In the lower left corner is a Daphnia, also known as a “water flea”. I reconstructed the image in depth from 0-15mm in increments of 250 microns. See **Appendix A** for specific camera settings and program data entries.



See all 60 reconstructed images at http://pegasus.me.jhu.edu/~lefd/shc/LPholo/stills.htm

Movies

Below is a frame from an mjpeg movie recorded at 30fps and resolution 16 microns/px.



Original size is 640x480, Color. The movies could only be taken in color and saved in an mjpeg avi format; I converted them to grayscale in Videomach[2] after downloading an mjpeg DirectX codec[7] (already included on Windows XP). I reconstructed the Daphnia in the lower right of the image in depth from 0-15mm in increments of 250 microns, however none show the creature in focus. See **Appendix B** for specific program data entries.

Download a sample movie at http://pegasus.me.jhu.edu/~lefd/shc/LPholo/fuzzymovie.avi

This is the original (not reconstructed) file except already converted to grayscale. Even though it does not focus, it does show the behavior of the Daphnia.

Original Image

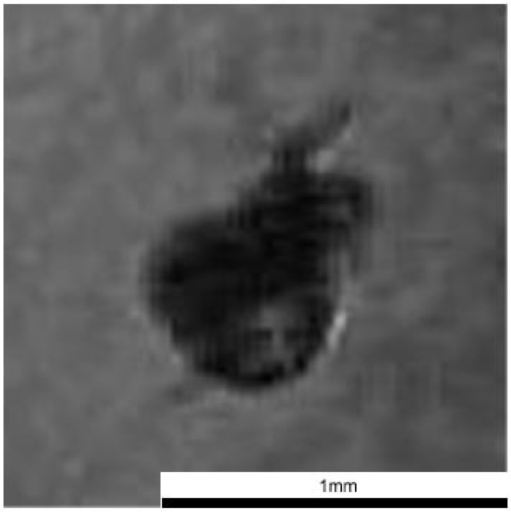
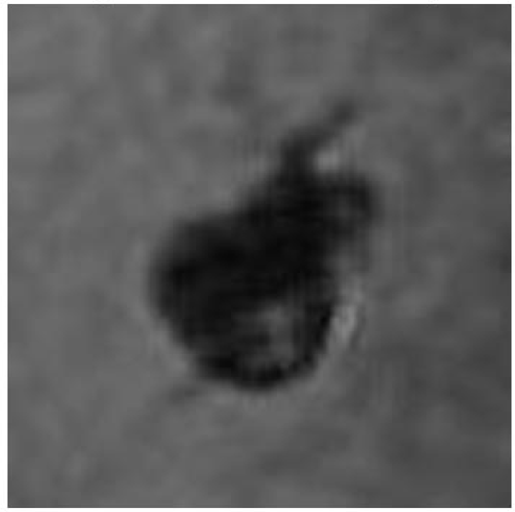
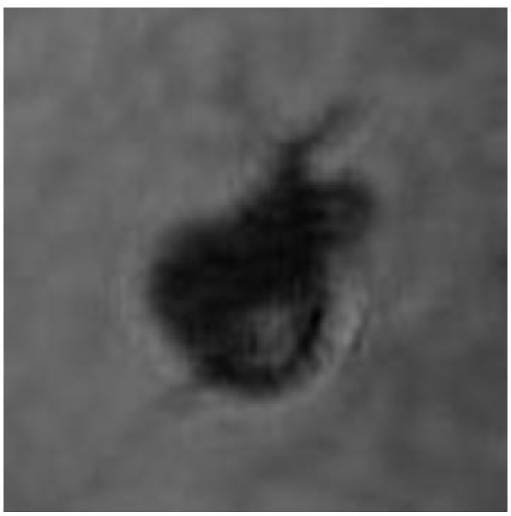


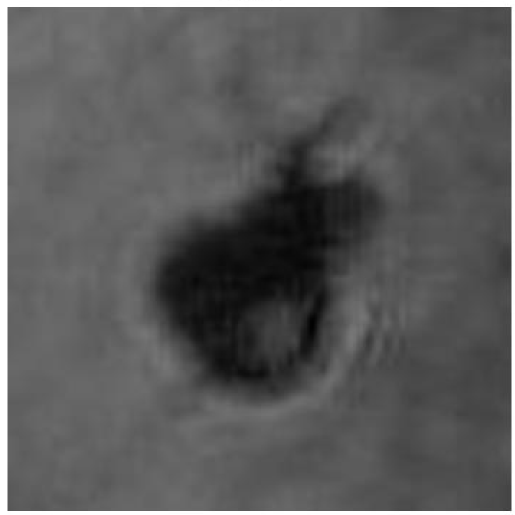
Image Reconstructed at 3mm depth



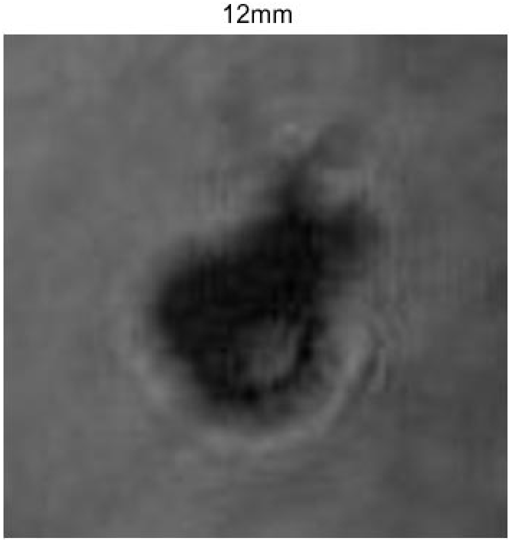
6mm



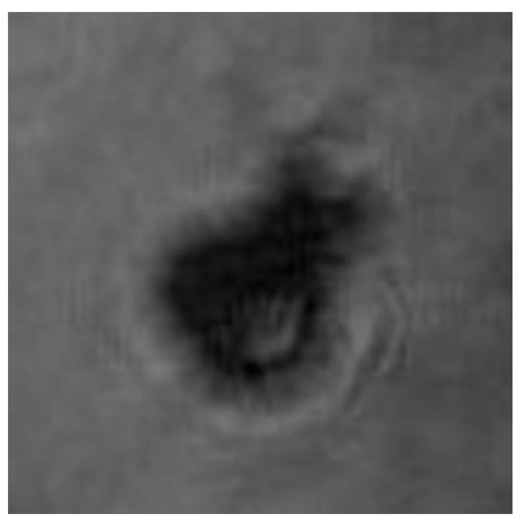
9mm



12mm



15mm



Results and Conclusions

The point of this project was to examine the feasibility of low-cost holography. Can you record viable holograms? How much does it cost? What are the major difficulties?

The reconstructed still images in the **Data** section of this paper show the success of this experiment. The daphnia does clearly come into focus, and although I have seen much nicer images generated by the high-level systems in our lab, this is not bad. In the close-up image set as well as the full frame (available online), you can see other objects coming into focus, notably several small particles near to the Daphnia in our field of view, located at 3mm and 9mm depths.

I was most interested in recording movies of the plankton, however the resolution of movies recorded with this camera was just not good enough. If the lenses were moved in order to magnify the target significantly, it may be possible to get better results. Not being able to remove the camera lens was a major hindrance, because it required another lens to counteract it, made calculating the magnification a tricky proposition, and prevented me from being able to see for certain whether the laser light was collimated, expanding or focusing when it hit the CCD.

The laser pointer itself is the cheapest part of this system- only $10! It has a coherence length sufficient to produce a distinct interference pattern (unlike LEDs), which is what we need for holography. The manufacturer of this specific laser pointer is Lazerpro.

Lenses similar to the expanding and focusing lenses used in this system can be obtained for around $50. The large collimating lens I used is a different matter- it costs hundreds of dollars. This is not a fatal problem however, because a smaller diameter lens can be used and the field of view will just be smaller. An optical rail and mounts to hold the optical elements could cost another $100 or less.

I used the Fujifilm Finepix S602 because it was available. It sells for around $600 online. It has some very nice features (the SP mode lets you record black and white still images, which reduces compression and saves the trouble of converting them from RGB later). A removable-lens digital camera would be ideal, as I mentioned above. A higher resolution movie mode is also very desirable.

Assuming you already have a digital camera or can borrow one, you can build a laser pointer holography system for $300. This is the major advantage to digital holography- no expensive film and no strange (and sometimes carcinogenic) developing procedures.

In the future, low cost submersible holographic systems could be deployed routinely by biologists to monitor plankton in their natural environment. The only hindrance is currently the camera, and high resolution digital cameras are becoming cheaper everyday. Soon even cell-phone cameras might be used for holography!

References

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   Edwin Malkiel, Jian Sheng, Joseph Katz, and J. Rudi Strickler

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   http://www.gromada.com/videomach.html

3. Fujifilm Finepix, Tiff format

   http://www.finepix.de/en/3_300_1017754714.html

4. Digital Photography Review, Sensor Sizes

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5. Fujifilm, Finepix S602Z manual

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6. Fujifilm, 3rd generation Super CCD chip specifications

   http://www.fujifilm.com/JSP/fuji/epartners/bin/3rdGenSuperCCD_2.pdf

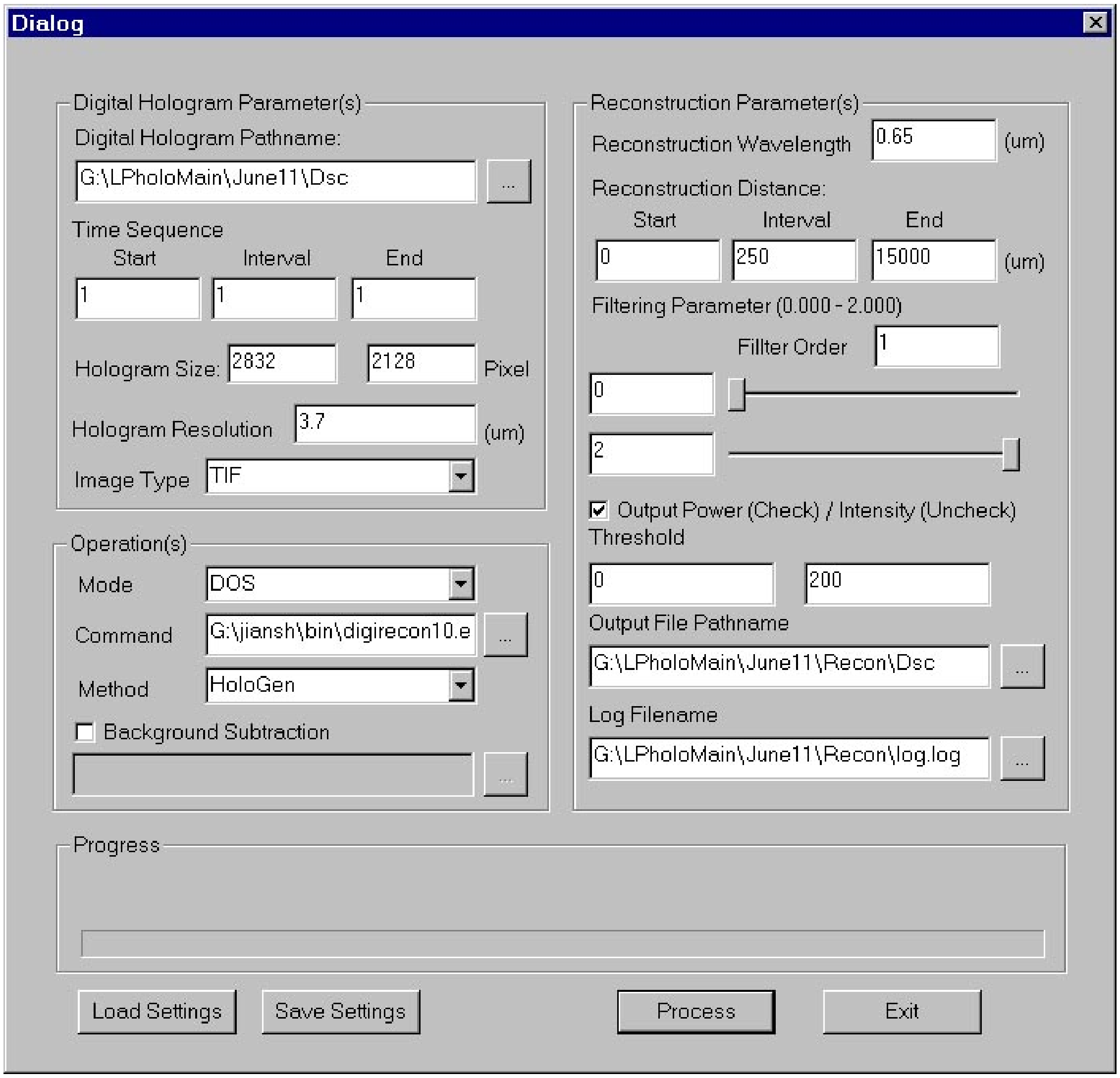
7. Windows Media Player, FAQ

   http://www.nwlink.com/%7Ezachd/pss/pss.html - mjpeg

Appendix

A. The still images were captured with the Fujifilm Finepix S602Z fully zoomed in and set to SP mode, Black and White, Manual Focus, max resolution (2832x2128 Tiff format).

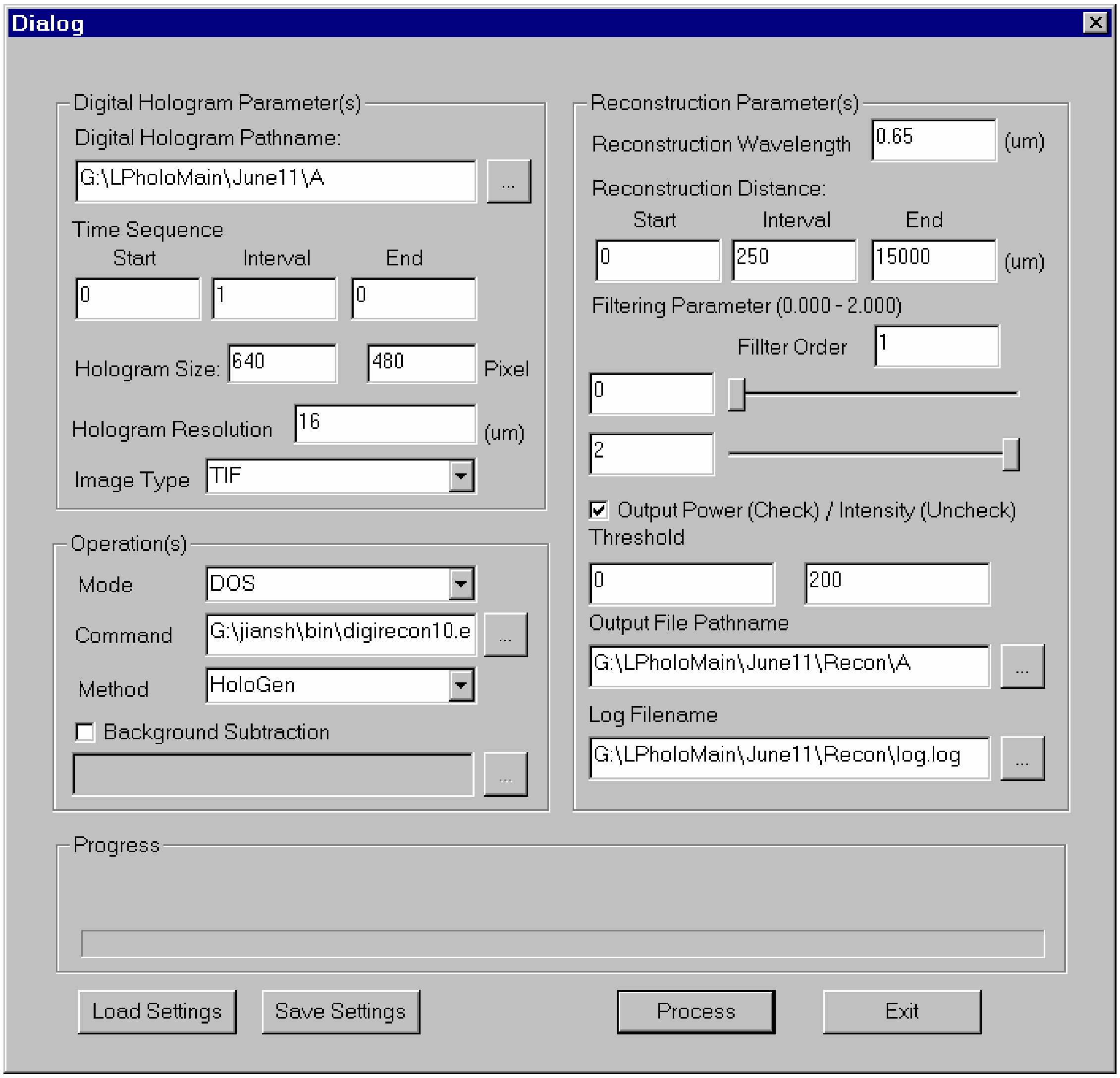
'DigiHoloWin' reconstruction program:



Here the input image file is named Dsc_001.tif

B. The movies were captured with the Fujifilm Finepix S602Z fully zoomed in and set to movie mode, VGA output, only available file size 640x480 avi. Focus is set just before recording. I converted the movie to a list of grayscale tiff files in Videomach[2] before running this program (required).

'DigiHoloWin' reconstruction program:



Here the input image file is named A_000.tif