# Proposed Digital Holographic 3-D mapping of Coral Beds

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## ABSTRACT

Digital Holography is a technique which provides a measurement of the complex field reflecting from a coherently illuminated object. When the measurement is performed with two carefully chosen wavelengths a phase difference map can be created providing a three dimensional map of the object. We present results from a laboratory experiment where the surface contours of coral are measured in seawater. Contour maps with step sizes on the order of 0.1 mm can easily be obtained. We propose that this technique be used to remotely monitor the growth of coral in an effort to quantify the health of coral beds. The technique is effective from space, aircraft, ships, buoys or rigid platforms such as a pier. In the last few years we have been successfully using this technique to measure objects through very turbulent atmosphere at ranges of up to 700 meters and we are now applying the concept to shoreline applications.

**Keywords:** Spatial Heterodyne imaging, Holographic Laser Radar, Underwater Imaging

## 1. INTRODUCTION

The United States National Oceanic and Atmospheric Administrations Coral Reef Conservation Program (CRCP) has the following organizational goal: "*The primary goal of the CRCP is to protect, conserve, and restore coral reef resources by maintaining healthy ecosystem function"*. Fundamental to achieving this goal is a set of tools that enable oceanographers to monitor the health of coral reefs. Many techniques have been used to monitor the health of coral beds. Spectroscopic imaging enables the remote detection of coral bed general health [1]. Laser Induced Fluorescence spectroscopy provides a measure coral bleaching [2]. Other techniques such as Streak Tube Imaging Lidar [3] provide a means of measuring the size of coral reefs in 3 dimensions however the range resolution of such systems are limited by pulse width and sampling rate. We will focus on 3-D mapping of coral beds as a technique for measuring coral health prior to bleaching. This requires a measurement technique that has a resolution of tenths of millimeters. High resolution measurements enable the detection of a slowing in growth which would be a precursor to coral health decline. Digital Holography is a technique by which three dimensional maps can be acquired with 0.1 mm resolution.

Previously, we described a technique for measuring the surface contours of Jupiter's moon Europa [4]. We proposed Digital Holography as a means for producing three dimensional maps with vertical resolutions on the order of a millimeter. Measurements made in the absence of atmospheric turbulence are greatly simplified since there are no temporally varying wavefront aberrations other than instrument variations. We have refined our digital holographic approach for use in environments with deep turbulence. The technique is independent of the turbulent medium meaning that atmospheric turbulence effects as well as hydrodynamic turbulence effects are correctable. This technique provides a non-destructive, non-contact technique for early warning of the decline in the growth of the coral bed.

Digital Holography has been developed extensively over the past five years. The main focus of this work has been to develop imaging systems for situations that have deep atmospheric turbulence. Examples include horizontal path imaging a few meters above the ground. This has been demonstrated at ranges approaching one Km. Digital Holography enables the correction of the atmospheric turbulence after the data has been acquired. There is no need for deformable mirrors or any type of active compensation. Our experience with Digital Holography in extreme atmospheric turbulence leads us to the conclusion that the same techniques can be employed in situations where optical

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turbulence is extreme. In general coral does not grow below 50 meters. Most of the imaging we are suggesting will take place over not more than a 20 meter water path. The non-water path will be as much as 100 Km but the atmospheric turbulence effects from this will be correctable.

Variations in the optical path length in seawater are similar to atmospheric turbulence in that the majority of the turbulence is caused by thermal variations in the medium. An added complication to seawater is that inhomogeneous salinity will also cause turbulence. Salinity variations will be most acute after rain storms and in areas where freshwater springs come up from the ocean floor and where freshwater streams enter the ocean.

Figure 1 is a plot showing the variation in seawater index of refraction as a function of both salinity and temperature. These are calculated using equations derived in reference [6]. The index varies by about 8E-5 per degree C. The variation with salinity is much more benign although after a rain storm their will be significant variations near the surface.

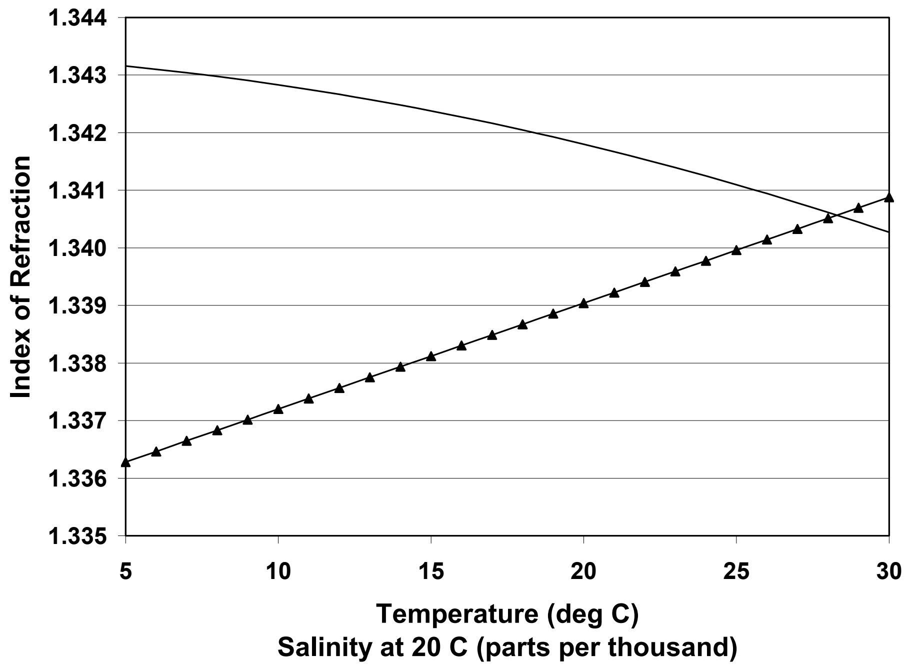



Fig. 1. The index of refraction of seawater for light of wavelength 532 nm. The solid line ( —— ) is the index as a function of temperature. The small triangles (—▲— ) show the index for 20 degree C seawater as the salinity varies. Variations are in the 3rd decimal position.

For comparison Figure 2 is a plot of the variation of the index of refraction of air as a function of temperature. These values are calculated from reference [7]. For air the variation of index is about 1e-6 per degree C. For a measurement of coral over a twenty meter seawater path and a 1600 meter air path the product of dn/dt and range is equivalent. In this case the turbulence due to the two paths will be similar provided the thermal in-homogeneities and turbulence strength are similar. There will be the added path length variations due to the surface topography of the ocean but these will manifest as image stretching artifacts which are easily corrected using standard affine transformation algorithms.

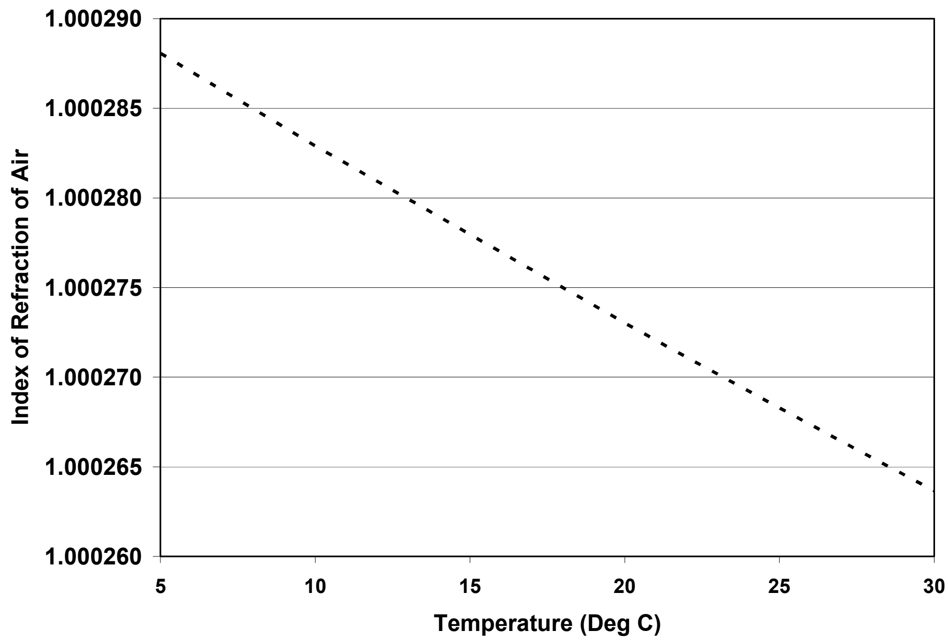



Fig. 2. The index of refraction of air with 50% humidity for light of wavelength 532 nm. Variations are in the 5$^{th}$ decimal position.

An example of the effect of severe atmospheric turbulence on a 0.532 micron laser over a 700 meter air path is shown in figure 3. We are currently able to correct for these effects [5] and we propose using the same algorithms for oceanographic optical turbulence that have been developed for deep atmospheric turbulence.

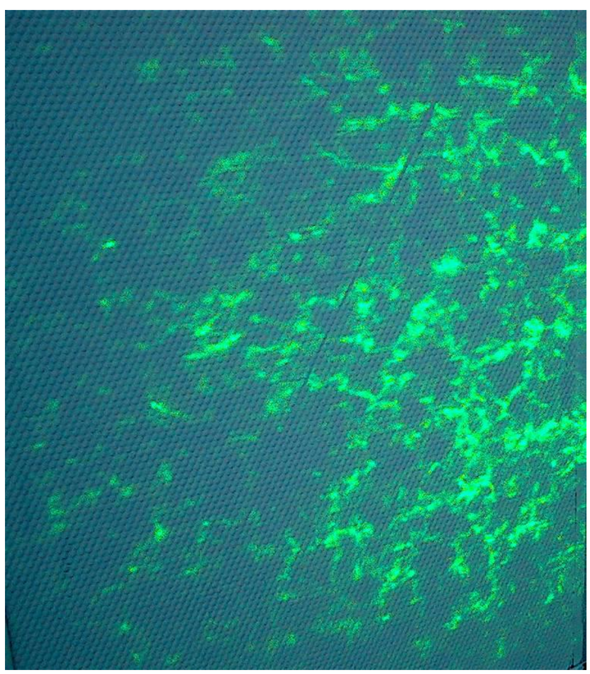


Fig. 3. Atmospheric turbulence effects are shown for a 0.532 micron laser that is traversing a 700 meter air path approximately 1 meter above the desert floor. The visual effect is very similar to the effects on sunlight as seen in shallow water.

## 2. CONCEPT DESCRIPTION

Digital Holography has been described in detail in references [8] and [9]. We give a brief description and list the governing equations in this paper. There are three equations that are used to define a digital holographic imaging system. The lateral resolution of a digital holography camera is the same as for a standard imaging telescope.

$$\text{Lateral Resolution} = R\ \lambda/D \tag{1}$$

Where the illuminator wavelength is $\lambda$ , D is the aperture of the imaging telescope and R is the target range. Range measurements are made by varying the wavelength of the illuminator laser and then creating a phase difference map. The total range over which the illuminator laser is tuned defines the range resolution.

$$\text{Range Resolution} = \lambda^2 / (2\ \Delta\lambda) \tag{2}$$

Where $\lambda$ is the wavelength of the illuminator laser and $\Delta\lambda$ is the total wavelength range over which the illuminator laser is tuned. There is an ambiguity range which defines the distance over which any discontinuities in the object can be unambiguously determined. This range is given by

$$\text{Ambiguity Range} = \lambda^2 / (2\ \Delta\lambda_{inc}) \tag{3}$$

Where $\lambda$ is the center laser wavelength and $\Delta\lambda_{inc}$ is the wavelength increment as the laser is stepped in wavelength. For most applications there is only a need for two wavelengths and the spread between them will determine the range over which there are no two pi ambiguities.

Using these three equations we can define the system parameters for a coral imaging system operating from a range of 2000 meters. Using a 0.5 meter telescope and a wavelength of 0.532 microns we will have a lateral resolution of 2.13 mm. In order to have a 0.1 mm range resolution a wavelength increment of 1.415 nm is required. The is easily accomplished using Optical Parametric Oscillator (OPO) technology. If wavelength step sizes of 0.1415 nm of the laser are used then the ambiguity range will be 1 mm. An important strength of the DH technique is that the range resolution and ambiguity range can be varied by adjusting the wavelength step size of the laser. This can be changed during operation so that a variety of targets can be imaged.

The Digital Holography technique can be used to measure the relative growth of particular areas in a coral bed. These could be tracked over time to create a growth map. For example figure 4 is a photograph of brain coral. A three dimensional map of the brain coral could be constructed and monitored weekly to determine the growth rate as compared with the surrounding coral. The monitoring could take place from a small skiff or a small airplane. A space based system could also be used for periodic coverage.

Fig. 4. An example of brain coral is shown. Digital Holography could be used to monitor the growth of the brain coral continuously from a fixed platform or periodically from a variety of remote sensing platforms.

## 3. EXPERIMENT

Figure 5 is a diagram of the lab experiment setup. A tunable laser is split into two beams. One beam illuminates the target which is coral in this case. The other beam is retro-reflected back on itself as the reference beam or local oscillator. In this experiment two wavelengths are used to illuminate the coral. Three dimensional maps of the coral are created at each wavelength and differenced for a 3-D topographic map of the coral.

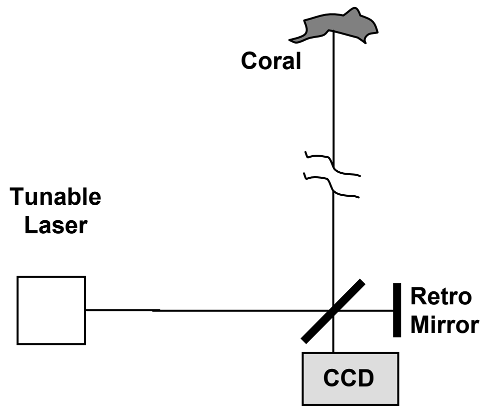



Fig. 5. A schematic of the laboratory experiment is shown with the major components labeled. A beam splitter is used to create an illuminator beam and a reference beam.

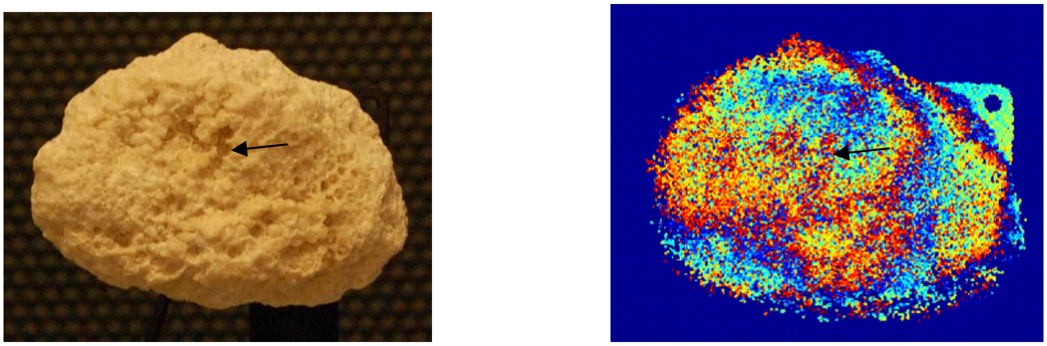
Figure 6 is a photograph of the object used in the experiments. A small plastic tank filled with seawater is used as a simulation of coral just slightly underwater. A piece of fossilized coral is used as the test target. A small plastic model of a submarine was added to the scene to the scene as a calibration object.

Fig. 6. A piece of fossilized coral is used as the test target. A plastic model of a submarine is included for spatial reference. The tank is partially filled with seawater.

## 4. RESULTS

Figure 7 (a) is a photograph of the piece of fossilized coral used in the test. The coral was imaged before placing in the seawater tank. Figure 7 (b) is a representative 3-D map of the coral. Note the bracket imaged in the upper right corner.

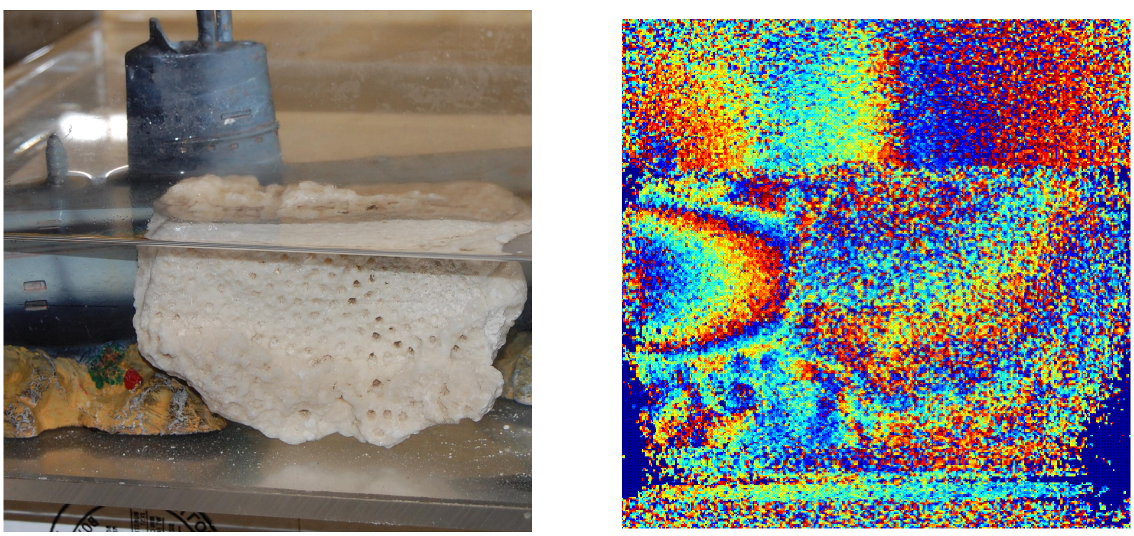
The surface is plotted in a rainbow colors where one ambiguity range spans from dark blue to dark blue and is approximately 1 cm. A small arrow in each image points out a reference feature.



**a** **b**

Fig. 7 a) A photograph of the piece of coral used in the experiment is shown b) the measured 3D map of the coral is shown.

Figure 8 (a) is a photograph of the coral in the seawater tank. This is approximately the area that is illuminated by the laser. Figure 8 (b) shows the 3-D map of the coral and submarine. Again the 3-D map is shown in rainbow colors where one fringe is approximately 10 mm. The rounded side of the submarine can clearly be scene as can the fine structure of the fossilized coral. The depth resolution in these images is approximately 0.1 mm although it is difficult to see this because of noise in the images. Note that there is a discontinuity between the submarine surface and the surface of the coral. The discontinuity is larger than the ambiguity range so that there is no information about what the step size. However, by adjusting the wavelength step increment the ambiguity range can be increased.



**a** **b**

Fig. 8 a) The coral and submarine are shown in a tank of seawater. b) A The surface map of the coral is shown. The bulls-eye pattern to the left of the image spans a range depth of approximately 10 mm.

## 5. CONCLUSIONS

We have demonstrated a very rudimentary example of imaging coral in seawater. Our work in horizontal path imaging gives us confidence that algorithms developed for atmospheric turbulence can be adapted for use in underwater imaging. Figure 9 is a photograph of a typical underwater coral bed with a schematic of a Digital Holographic Camera illuminating the coral bed. Optical aberrations caused by atmospheric turbulence, sea surface waves, hydrodynamic turbulence and salinity variations all need to be corrected in order to produce an accurate three dimensional map of the coral bed. Our work in correcting severe atmospheric turbulence gives us confidence that all of the aberrations induced along the air seawater imaging path can be corrected in post-processing using Digital Holography. Our techniques enable the measurement of the relative growth rate of the individual coral growths as well as an absolute growth rate with respect to the seabed.

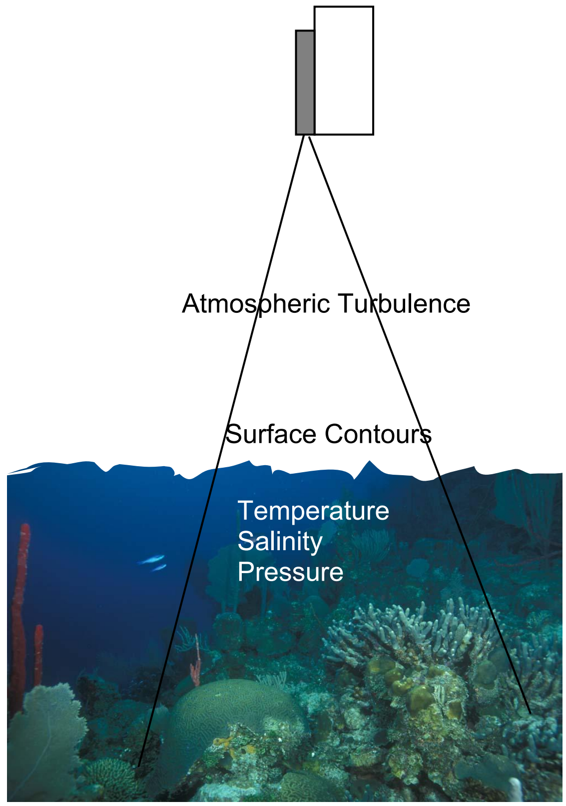



Fig 9. Brain coral is shown growing near other forms of coral. Relative growth rates are easily measured between different samples of coral. Absolute growth rates are measured with respect to the seabed. Correction of the effects of atmospheric turbulence, surface contours, and the temperature, salinity, and pressure along the optical imaging path must be corrected.

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