

Imaging Coral II: Using Ultrasound to Image Coral Skeleton

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We report on imaging of coral skeletal densities using pulse-echo ultrasound. Focused ultrasound transducers with frequencies ranging from 1 to 5 MHz were used to image coral skeletal samples. Each transducer was scanned over the surface of a coral and the reflected signal from the coral was recorded. Post-processing of the ultrasound signal was used to generate images of the acoustic impedance of the coral—a quantity that is related to the density of the coral. The ultrasound images were qualitatively consistent with X-ray images of the coral samples—X-ray absorption is also related to coral density. Both images showed a banding structure related to the annual growth cycle of the coral. The results indicate that ultrasound can be used for nondestructive imaging of coral skeletal structure. The ultimate goal would be an *in situ* system for quantitatively measuring skeletal densities of live corals underwater. The skeletal density of several massive reef coral species is strongly correlated with ocean temperature. A time series reconstructions of the skeletal density of long lived specimens would provide a history of surface ocean temperatures over time periods extending over several centuries, far beyond the available instrumental record.

Key Words. Ultrasound imaging, coral, nondestructive evaluation, NDE, growth bands.

1. Introduction

The aragonitic skeletons of massive reef corals are a valuable source of information about the history of sea surface temperature (SST) variability

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in the tropics and subtropics, and have been used to address some particularly important climate change questions. The abundance of large coral colonies, their rapid continuous growth (1–2 cm/yr for Pacific porites) and extraordinary longevity (a single colony may live as long as 1000 years [1]), offer the potential to reconstruct multicentury-long SST records at seasonal, and sometimes weekly, resolution. Information about major climate phenomena such as El Niño-Southern Oscillation, Asian Monsoon and the North Atlantic Oscillation which impact the temperature of the surface oceans, is locked into the coral skeleton as it grows, preserving a detailed history that is unobtainable from any other source [2–4]. Much of the information that is currently accessed in the form of changes in skeletal chemistry, for example, the oxygen and carbon isotope ratio ($\delta^{18}\text{O}$, $\delta^{13}\text{C}$) and trace element composition (Mg/Ca, Sr/Ca ratios) of the skeleton are temperature sensitive [5] and techniques have been developed to measure these changes with the precision necessary to resolve temperatures to a few tenths of a degree.

The density of coral skeleton is also sensitive to changes in ocean temperature and recent efforts have begun to explore its utility as a paleoclimate proxy [1,4,6,7]. That skeletal density changes seasonally, probably in response to seasonality of light and temperature [8], has been known for several decades [9]. The resulting annual growth bands, consisting of one high and one low density band, are visible in X-radiographs and used to establish first order chronologies for coral-based climate records. The structural (physical) basis for density variations seen in X-ray images are changes in the relative thickness of interconnected vertical and horizontal skeletal elements of the corallite and resulting changes (on the scale of mm) in the size of the skeletal pore spaces [4,10]. In the subtropical North Atlantic and Caribbean, corals tend to accrete thicker skeletal elements with smaller pore spaces during the warm months, and thinner elements with larger pore spaces in the cool months [4,10]. In X-ray, these regions appear as alternating bands of high and low density skeleton, respectively. These high-frequency, seasonal changes in skeletal density are superimposed upon low frequency changes that occur over several years. In the subtropical North Atlantic and in the southwestern Pacific (GBR) low frequency changes in skeletal density of massive *Diploria* (brain corals) and *Porites* colonies have been shown to correspond with interannual and decadal scale variability in ocean temperature [1,4,6,7].

Measurement of skeletal density as a temperature proxy has several advantages over traditional geochemical proxies. These include increased temporal resolution of the proxy record (for example, subsampling techniques for oxygen isotope analysis enable records to be produced with monthly or bimonthly resolution, compared with weekly resolution with image analysis), skeletal density can be 5 times more sensitive to changes in ocean

temperature than are skeletal isotope or elemental ratios (this is especially useful at mid-latitude sites where interannual variability is on the order of 1°C or less) [4], and image analysis is cheaper and quicker than chemical analyses (this is especially important because there is a need to produce more than one proxy record at a particular site; expense of chemical analyses may prohibit replication of records). For these reasons, we are currently working to develop the density-based paleothermometer as a standard paleoceanographic tool. One of the limitations imposed by the current technology used to image skeletal density (i.e. conventional X-ray) is that it cannot be used underwater, i.e. *in situ*. An *in situ* imaging modality would obviate the need to recover large corals from the seafloor.

Ultrasound is a modality that has the potential to image coral *in situ*. We report experiments using megahertz ultrasound, employing non-destructive evaluation (NDE) tools [11,12], to measure the structure of two different species of coral. Ultrasound is a mechanical probe that penetrates into any compressible material and as such directly interacts with the structure of interest in coral. The propagation and reflection of ultrasound primarily depends on the local density and sound speed of the medium and it is the variation in these properties that is studied here. In addition, ultrasound is affected by the scale and orientation of structure—particularly when the spatial length of the structural variability is of the order of a wavelength. Therefore ultrasound has the potential not only to provide information on density but may also be able to provide information about the structure of coral.

2. Experimental Procedure

Coral samples were obtained from specimens that had been previously removed or sampled from a reef. The samples took one of two forms, either (1) a flat section (10 mm thick) that had been cut from a large round colony using a water-cooled tile saw fitted with diamond tipped blade or (2) a cylindrical core that had been removed from a living colony using a diver-operated hydraulic underwater corer, fitted with a 75 cm long double tube core barrel and detachable tungsten carbide drill crown [13].

X-radiographs of the coral slices were taken at the local hospital (Falmouth, MA) using the following settings: 50 kV, 1.6 mAs, a 1 m film focus distance and an 0.25 s exposure onto extremity film. ScionImage (Scion Corp, Frederick, MD) was used to assign grayscale intensity values to scanned X-ray positives and construct the density profiles. We did not attempt to correct for the heel effect, the non-uniformity of an X-ray beam across the diameter of the cone of radiation [14]. However, we utilized a long film focus distance which combined with the small size of our samples, was

Table 1. Nominal properties of the ultrasound transducers used in these experiments.
The wavelength is that calculated in water with a sound speed of 1500 m/s

Model number	Frequency (MHz)	Wavelength (mm)	Focal-length (mm)	Transducer diameter (mm)	Focal region length (mm)	Focal region diameter (mm)
V302	1	1.5	38.1	25.4	52.5	5.49
A306S	2.25	0.667	25.4	12.7	42.0	3.25
V380	3.5	0.429	50.8	25.4	27.0	2.10
A306S	5	0.3	25.4	12.7	18.9	1.46

intended to minimize the heel effect by utilizing the central beam area where intensity is uniform.

Ultrasound imaging was carried out in a large water tank. The tank was filled with deionized, degassed water. The coral sample was held fixed in the tank during ultrasound measurements. An ultrasound transducer was mounted onto a three-dimensional motorized stage and scanned under computer control. The transducer was used in pulse-echo mode and reflections from the coral were recorded and stored.

Four different spherically focused ultrasound transducers (Panametrics, Waltham, MA) were used in this study. The centre frequency of the transducers varied from 1 to 5 MHz and the geometric focal length varied from 25.4 to 50.8 mm, see Table 1. The focal region of a focused transducer is not a point but is a cigar shaped volume around the geometric focal point. The length of the focal region in the direction of the acoustic beam is given by

$$\Delta_z \approx \frac{\lambda}{\sin^2(\alpha_{\max}/2)} \quad (1)$$

where $\alpha_{\max}$ is the half angle of the transducer aperture. The diameter of the focal region, lateral to the beam direction is given by

$$\Delta_y \approx 1.22 \frac{\lambda}{\sin \alpha_{\max}} \quad (2)$$

The focal region length and diameter defined here are both determined based on the location of the zeros of the pressure field that are closest to the geometrical focal point.

For the pulse-echo mode used in these experiments, the same transducer was used to transmit the interrogating pulse and receive any scattered echoes. To a first approximation the transducer is sensitive only to acoustic signals from the focal region. Therefore, only objects present in the focal region will generate echoes that can be detected by the transducer. Objects outside the focal region will not be detected. The resolution in the axial direction of the transducer can be enhanced by using time gating and

is discussed below. The lateral resolution cannot be improved beyond the dimension given in Eq. (2).

The amplitude of the echoes can be related to the local density by considering the case of a plane wave normally incident on a plane surface. The pressure amplitude of the reflected wave p_R in terms of the amplitude of the incident wave p_I is

$$p_R = p_I(Z_2 - Z_1)/(Z_2 + Z_1) \quad (3)$$

where Z_1 is the specific acoustic impedance of the first medium and Z_2 the specific acoustic impedance of the second medium. The specific acoustic impedance is defined as $Z_i = \rho_0 c_0$, where ρ_0 is the density and c_0 the sound speed of the medium. Note for the rest of this manuscript we shall refer to Z simply as the impedance. For water the nominal values of density and sound speed ($\rho_0 = 1000 \text{ kg/m}^3$ and $c_0 = 1500 \text{ m/s}$) yield an impedance $Z = 1.5 \times 10^6$ Rayls. The water–coral interface will induce a reflected wave with an amplitude that depends on the impedance ($\rho_0 c_0$) of the coral, that is, the amplitude of the reflection does not depend solely on a change in density. We note that measurements on human cancellous bone indicate that sound speed and density are strongly correlated [15] and therefore the impedance can be correlated with density. Because cancellous bone has a very similar structure to coral [16], we anticipate that the acoustic impedance of coral can also be directly related to coral density and the amplitude of the reflection from the coral surface can be used as a proxy for density.

The simple reflection model described above breaks down if the surface is not normal to the incident wave or if it is not plane. In particular, if the interface between contrasting media has spatial features that vary on the order of an acoustic wavelength, the incident plane wave can be scattered in all directions and the amplitude of the backscatter becomes strongly dependent on the size of the object—scattering from spheres and cylinders is an example of this [17,18]. Because the surface of the coral is not smooth we anticipate that the interrogating pulse used in this study will undergo scattering over a wider angular region than assumed in plane wave theory. This rough surface interaction is beyond the scope of this study and the processing was carried out on the basis of plane wave interaction. However, we note that a processing model that can account for spatial features of the coral surface may be able to yield enhanced imaging of the coral.

Before ultrasound imaging was attempted it was necessary to ensure that the samples were fully saturated with water as the presence of gas bubbles strongly influences the propagation of ultrasound. Because the coral samples had been dried for the machining process it was necessary to re-saturate them prior to ultrasound imaging. This was achieved by submerging the samples in a beaker full of deionized water. The beaker was then placed

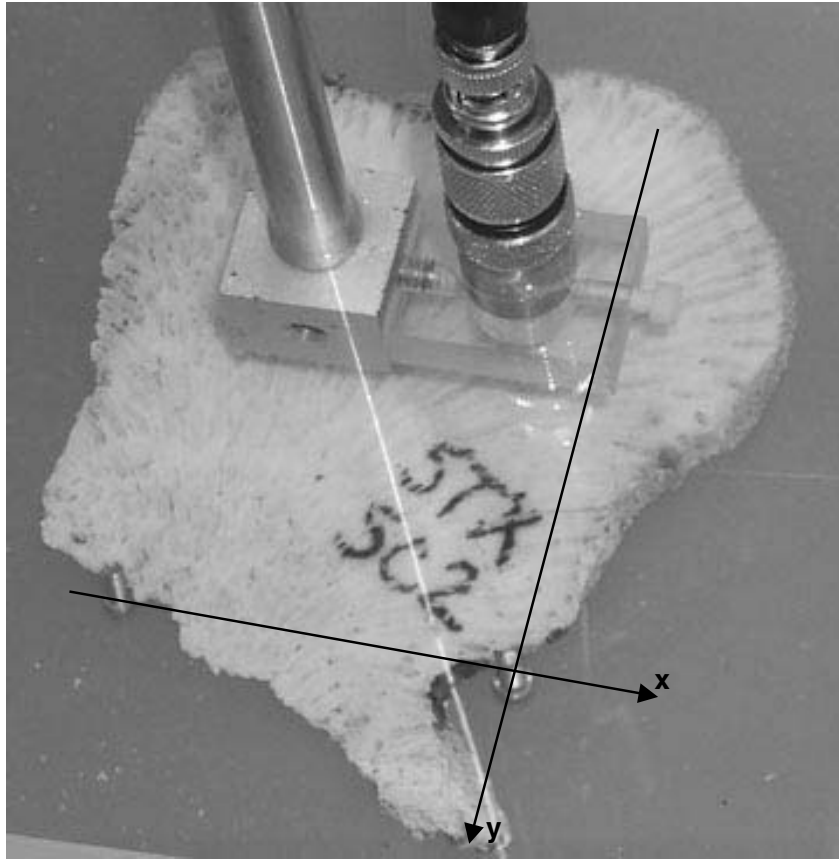


Figure 1. Picture of the set-up for the imaging of a flat piece of *Montastrea faveolata* (sample STX SC2). The coral was held fixed in the water tank. A focused ultrasound transducer was mounted to a positioning system and was used in a pulse-echo mode to detect the reflections from the coral. The transducer was mechanically scanned in a two-dimensional raster scan over the surface of the coral. The x - y co-ordinate system is shown on the image. The metal screws were used as fiducial markers.

in a vacuum chamber and a vacuum (absolute pressure <3 kPa) was drawn for at least 24 h. The vacuum chamber was mechanically shaken regularly during the 24 h period to facilitate the detachment of gas bubbles emerging from the sample. At the end of the degassing period no visible bubbles appeared from the coral when it was shaken, and subsequent ultrasound scans revealed no evidence of gas pockets in the sample. The coral sample was transferred from the vacuum chamber to the ultrasound tank whilst still submerged in the beaker to ensure that it did not come in contact with air.

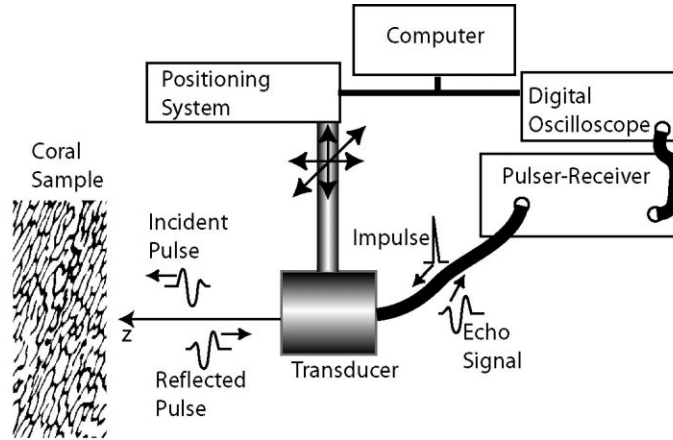


Figure 2. Signal path for the ultrasound scanning system. The pulser excites the transducer with a short electrical impulse. The transducer emits an ultrasonic pulse that is incident on the coral. The reflected echo signal detected by the transducer is amplified by the pulser–receiver, digitized by an oscilloscope and transferred to a computer. The computer was used to control a positioning stage that moved the transducer over the surface of the coral (x – y plane).

For the imaging experiments the transducers were positioned normal to the surface of the coral (see Fig. 1) at a distance such that the focus of the transducer was located at the proximal surface of the coral. The beam axis of the transducer was taken to be the z -axis. The set-up was such that the x – y plane was parallel to the surface of the coral. The transducers were used in a pulse–echo mode, see Figure 2. In transmit mode, a pulser–receiver (Model UA 5052, Panametrics, Waltham, MA) was used to excite the transducers with a short electrical pulse which resulted in an acoustic pulse that was about 1.5 cycles in duration. In receive mode, the pulser–receiver gated and amplified the reflected signals detected by the transducer. The echo signals were then digitized by an oscilloscope (Model LC334, Le Croy, Chestnut Ridge, NY), transferred to computer and stored on disc.

The amplitude of the echo signal from the coral was assumed to be related to the local density of the coral. Our analysis focused on the surface reflection because signals that originated from deeper in the coral needed to be compensated for the attenuation of acoustic waves by the coral. The surface reflection was selected by time-gating the received signal so that only echoes from a specific distance were analyzed. The distance from the transducer was determined from the time-of-flight (TOF) between the transmission of the initial pulse and the reception of the echo [11]. Because the intervening medium was water with known sound speed c_0 the distance from

the transducer could be calculated by

$$z = \text{TOF}/2c_0 \quad (4)$$

The properties for the transducers used in these experiments are listed in Table 1. The axial resolution is dependent on the pulse length and is approximately one wavelength for these transducers. The axial resolution determines at what scale surface topology will affect the reflected signal, for example, the 1 MHz transducer will not be sensitive to surface topology which varies on a scale of less than 1.5 mm. The lateral resolution is controlled by diffraction and is given by Eq. (2). Lower frequency transducers have a larger focal diameter, which limits the spatial resolution of the transducer (5.5 mm for the 1 MHz transducer). A higher frequency transducer is able to detect fluctuations in surface properties at higher lateral spatial resolution (1.5 mm for the 5 MHz transducer) but is also more sensitive to surface topology (structures of the order of 0.3 mm will scatter a 5 MHz incident pulse so that it is not picked up by the transducer).

In the studies carried out here the transducer was scanned using the positioning system in a two-dimensional raster pattern over the surface of the coral. Each individual echo signal (referred to as an A-line) was recorded at each location of the scan and saved to disc. The recorded data set was processed using Matlab to generate two-dimensional images of the coral. The method employed in processing these images is described in the results section.

3. Results

3.1. *Montastrea* Coral

The coral shown in Figure 1 was a slab cut from a small rounded colony of *Montastrea* spp. (sample STX SC2) collected live from shallow reefs on the north east side of St Croix (US Virgin Islands). This slab was cut from the sample that was approximately 110 mm wide by 130 mm tall and was machined with flat sides to a thickness of 10 mm.

Figure 3 shows a representative A-line measured in pulse-echo mode from the coral using a 1 MHz transducer. The reflection from the water-coral interface can be clearly identified at $t = 54 \mu\text{s}$. After the main reflection the signal consisted of a decaying coda that was apparently due to reverberation and multiple scattering within the coral structure. We were not able to detect a distinct reflection from the back wall of the coral indicating that the incident wave is very strongly attenuated (by absorption and scattering) as it passes through the coral structure. This is consistent with

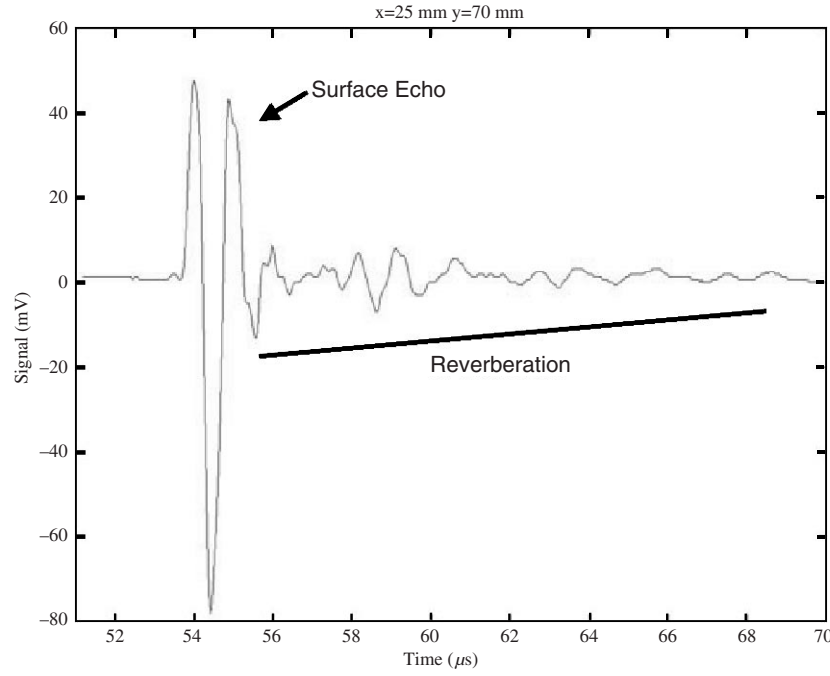


Figure 3. Representative A-line measured from sample STX SC2 using a 1 MHz transducer. The surface reflection occurs at $54 \mu\text{s}$ and is followed by a decaying signal due to acoustic reverberation within the coral structure.

through transmission experiments reported in the literature [16] and similar behaviour has been observed in cancellous bone that has a similar structure [19,20].

A B-scan of the coral was generated by scanning the transducer across the surface of the coral. The envelope of the A-line received at each location was obtained by calculating the Hilbert transform of the echo signal and taking the magnitude of the resulting complex signal. Figure 4 shows a B-scan obtained by moving the transducer in the y direction at $x = -50 \text{ mm}$ (refer to Fig. 5 for location on the sample). The gray scale represents the amplitude of the envelope of received echo as a function of the translation distance y (distance across the surface) and the distance from the transducer z (distance into the coral). The distance from the transducer was determined using Eq. (4).

The main surface reflection can be observed at $z = 45.5 \text{ mm}$ in Figure 4. The surface-reflection extends for about 1 mm (the axial resolution of the

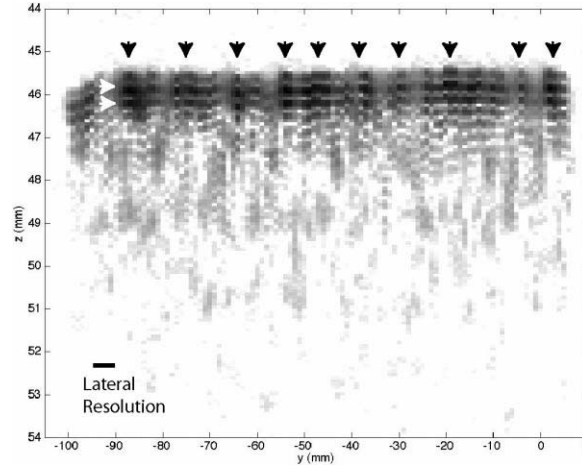


Figure 4. A 1 MHz ultrasound B-scan from sample STX SC2. The location of this slice with respect to the surface coral is shown on Figure 5. The gray scale was mapped to instantaneous amplitude of the envelope of the echo signal: black is high amplitude and white is low amplitude. Darker regions indicate a large reflection consistent with an echo return from a high density structure. The banding indicated by the white arrows is an artifact from the envelope of the received envelope. The banding structure indicated by black arrows is most likely due to changes in the local density of the coral. The backscattered signal from within the structure ($z > 46.5$ mm) is very weak and dies away within a few millimetres of the surface reflection. The horizontal bar indicates the lateral resolution of the transducer.

system) and the horizontal banding evident in Figure 4 is due to a periodic modulation in the echo envelope of the interrogating pulse. Variations in the amplitude of the reflection are dependent both on the local surface impedance and the local surface topology in the region of the width of the beam. We observed that the amplitude of the surface reflection exhibited a periodic nature (evidenced by the vertical bands) that could be attributable to banding structure in the coral. These bands appear “smeared out” because the lateral resolution of the system (indicated on the figure) was not small compared with the dimension of the bands that we seek to image. The coda seen in Figure 3 appeared as a low amplitude haze behind the front surface in Figure 4 and showed significant variation with spatial location. The amplitude of the backscatter will depend both on the local scattering strength of the coral and also how much attenuation the wave suffers whilst propagating into the coral and then propagating out again. In general we see that there is a stronger signal from deeper locations where the surface echo was weaker. This is consistent with the fact that if the surface echo is strong then there is

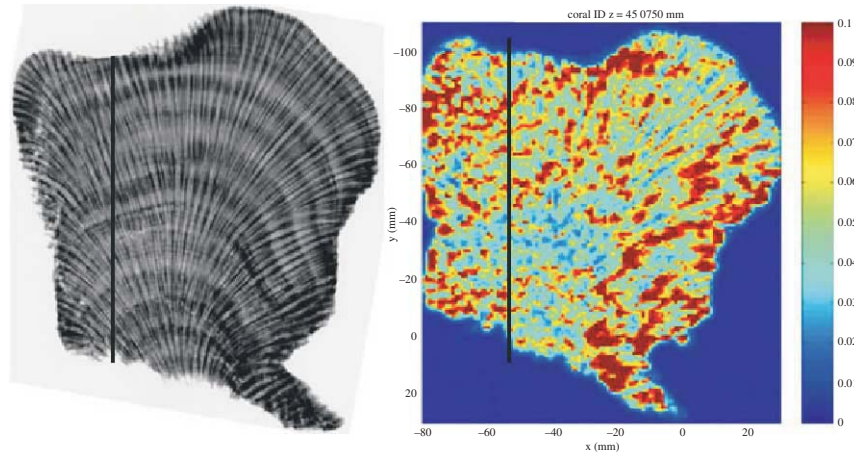


Figure 5. Left: X-ray image of sample STX SC2. The finer lines that emanate from the bottom centre are the tube-like corallites where the coral organisms live. The broader banding structure that is normal to the calices are the annual growth rings of the coral. Right: 1 MHz C-scan of the peak of the envelope of the acoustic reflection from sample STX SC2 over the surface of the coral: red indicates a large reflection and blue a small reflection. The red regions in the bottom right of the ultrasound image correlate well with the darker regions in the X-ray image. The fluting structure is evident in the upper right corner of the ultrasound image. In the central region the ultrasound image appears to reflect the banding structure observed in the X-ray image. The black vertical lines correspond to the position where the B-scan shown in Figure 4 was measured.

less acoustic energy transmitted into the sample and so the regions behind will be in a shadow region.

Figure 5 shows both an inverted X-ray image and a two-dimensional ultrasound image (C-scan) of the *Montastrea* coral. The inverted X-ray image reveals radial lines that originate at the base of the colony and fan out toward the top. These are tube-like structures called corallites that are accreted by, and house the coral animal or polyp. In this species, each corallite is occupied by a single coral polyp. Within the tube is a low-density scaffolding of vertical splines and horizontal (dissepiments) elements. Adjacent corallite tubes are separated by a denser wall of skeleton called the exotheca. Two types of structural variations are captured by the X-ray image. First, the outside wall of the tube is composed of the densest skeleton with least pore spaces, while skeletal structures within the wall (or tube) are less dense. Thus, the “outline” or traverse of each corallite can be seen in the X-ray. Second, the thickness of these skeletal elements changes seasonally and causes changes in skeletal density as the corallite grows. Each high and low density

couplet represents the annual growth of the coral. In this specimen, dark (high density) regions correspond to the summer time (June–August) when the ocean is warmer. In the light regions, the skeleton is less dense or “thinner” and is laid down over the winter months (January–March) [4].

The ultrasound C-scan was constructed by scanning the transducer in a two dimensional raster pattern over the surface of the coral. At each location an A-line was recorded. This data sets contains three-dimensional information about the sample: the translation gives x – y information and the time of flight for each signal gives depth z (see Fig. 2). The C-scan is an x – y map of the amplitude of the signal at a specific depth z . In Figure 5 the amplitude is the peak of the envelope of the surface reflection by gating the received signal with a $3.5\ \mu\text{s}$ (2 mm) window at the surface. The gating was done to exclude scattering from deeper in the coral. In the upper right hand corner of the C-scan image one can see fluting associated with the structure of the corallites. This correlates well with both the X-ray image and the optical image (Fig. 1). The broad regions of strong reflection in the lower right of the ultrasound image correspond with the darkened region in the X-ray image. The annual band structure is not as evident in the ultrasound image as in the X-ray image but it does appear to be present in the central region of the C-scan image.

3.2. Bazaruto Coral—*Porites lobata*

The set-up for ultrasound measurements of the Bazaruto (Mocambique) coral core sample is shown in Figure 6. The cylindrical core was 37.5 mm in diameter and 120 mm long. The ultrasound transducer was scanned in a two-dimensional plane over the curved surface of the coral. Note that we can only accurately measure the surface return when the transducer axis is normal to the coral surface, for otherwise the coral curves away and the reflected signal does not fully return to the transducer. For the sample used here we found that the width of the scan that resulted in a clear and accurate signal was <5 mm wide and positioned along the vertical centerline of the image.

Figure 7 compares the X-ray image and an ultrasound C-scan obtained using the 2.25 MHz transducer for the Bazaruto coral sample. The X-ray image is based on transmission attenuation through the entire sample thickness and no attempt has been made to correct for the fact that the coral path length diminishes towards the outer surface of the cylindrical sample. Therefore, the X-ray image, like the acoustical image, is reliable only along the image centerline. The ultrasound image is shown only for a region close to the centre-line—the region is indicated by the rectangle on the X-ray image.

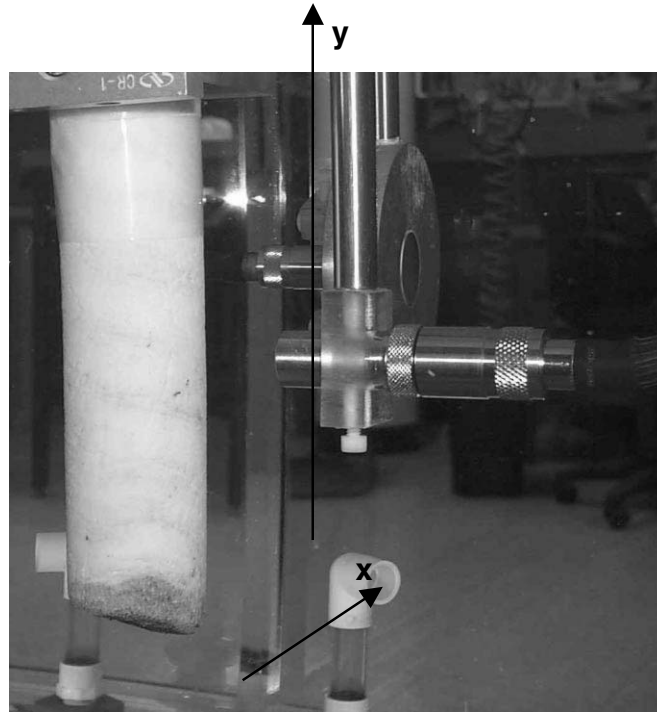


Figure 6. Set-up for the imaging of a cylindrical core of *Porites lutea* (Bazaruto). The plane of the raster scan is indicated by the axes.

The banding structure is present in both images and shows better correlation than was seen in the *Montastrea*.

The amplitude of the signal along the centerline of both images (with a width in both cases of approximately 1 mm) is shown in Figure 8. The X-ray grayscale intensity is a measure of total X-ray absorption through the thickness of the sample. The ultrasound reflection amplitude is the peak amplitude of the envelope of the received signal gated to the surface reflection. The two curves show some correlation with clear peaks at 10 and 16 mm. This correlation remains consistent through most of the depth of the sample however the fluctuations in the ultrasound signal are much larger than in the X-ray image. This may be partly because the ultrasound is affected by the surface topology. However, it could also be because the X-ray image yields the average density through the entire diameter of the coral whereas the ultrasound image is only representing the density at the surface of the coral. The former constitutes a much larger sensing volume and this could explain the reduced point-to-point variability seen in the X-ray data.

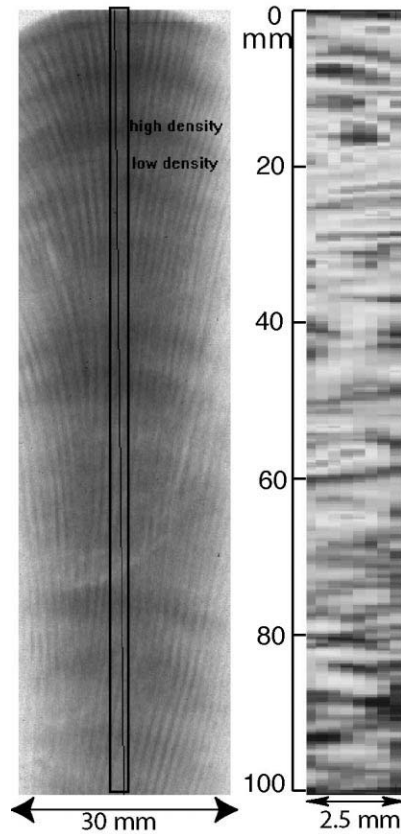


Figure 7. Bazaruto coral (*Porites lutea*). Left: X-ray image. Right: Ultrasound C-scan at 2.25 MHz. The ultrasound image corresponds to the black rectangle shown on the X-ray image. There is qualitative agreement between the bright bands in the ultrasound image and the high-density bands in the coral—particularly in the upper region. The thin black line on the X-ray image was the “centre-line” and is used in Figure 8. It is not parallel to the ultrasound box due to slight differences in image registration.

The effect of surface topology on the ultrasound signal can be demonstrated by comparing images using different frequency transducers. Figure 9 shows three C-scan images of the upper section of the Bazaruto coral from 10 to 40 mm measured using the 2.25, 3.5 and 5 MHz transducers. The large structures that are observable in the 2.25 MHz image appear to dissolve into smaller structures when the sample is imaged with the higher frequency transducers. This change in the nature of the images is because the microscopic structure of the coral is on the order of a few hundred micrometres.

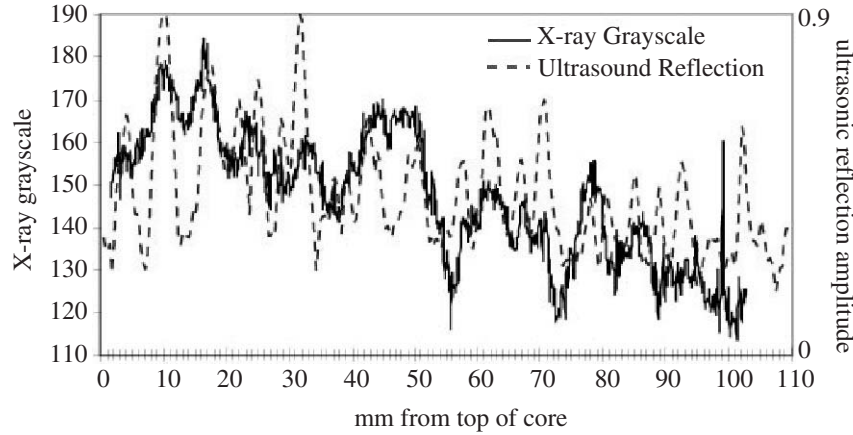


Figure 8. A comparison of the X-ray and ultrasonic measurements along the centre line of the Bazaruto coral. The X-ray grayscale intensity (solid line) was taken directly from the digitised X-ray image. The ultrasonic reflection amplitude (dashed line) was the measured amplitude of the envelope from the surface echo. The signals show good correlation in the peaks at 10 and 16 mm and good agreement with the location of peaks and dips elsewhere. The ultrasound derived intensity shows greater amplitude variation than that of the X-ray derived intensity.

For lower frequency transducers the wavelength is longer than the microscopic structures so that the ultrasound is unable to resolve them and the reflection appears to come from a medium that is homogeneous at millimeter length scales. For the higher frequency transducers the wavelength is small enough that it can resolve the fine structure and so the small channels and pores alter the reflection of the waves.

4. Discussion and Conclusions

The images shown here indicate that megahertz ultrasound has the potential to image the structure of coral. Lower frequency transducers (up to 2.25 MHz) were able to detect the banding structure associated with the annual growth cycle of the coral. The banding structure was consistent with the banding observed in X-ray images of the coral. High frequency transducers (above 3 MHz) could detect finer-scale microscopic structure of the coral.

We note that the X-ray and ultrasound images present information on somewhat different physical properties. The X-ray is an image of the total absorption through the thickness of the coral specimen. The ultrasound C-scan is an image of the reflection coefficient of the coral surface. Both

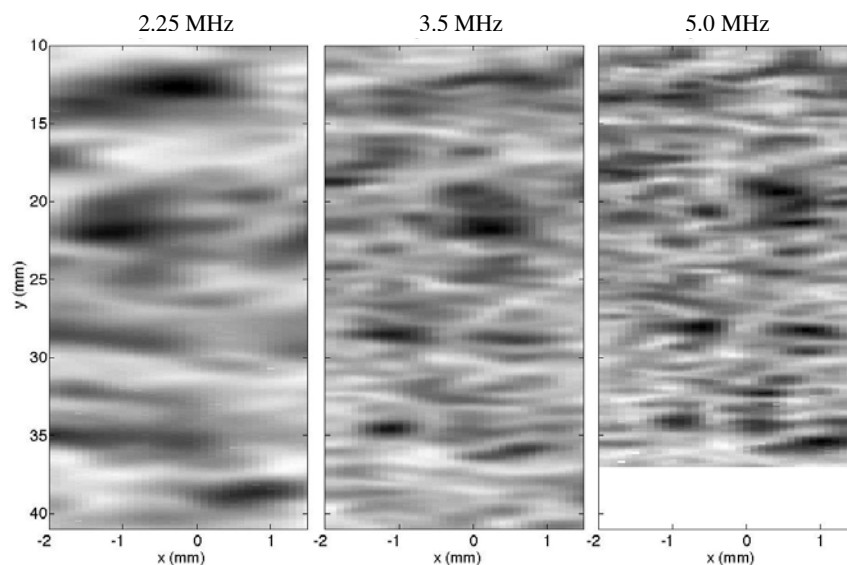


Figure 9. Ultrasound C-scan images of the upper 30 mm of the Bazaruto coral sample at three different frequencies: 2.25, 3.5 and 5 MHz. The 2.25 MHz image shows evidence of banding at $y = 12$ and 22 mm. In the higher frequency images this banding structure is shown to consist of structures on a smaller spatial scale.

of these properties are strongly dependent on the density of the sample. However, the X-ray image portrays mean density through the entire thickness of the coral whereas the ultrasound is related to the local surface properties.

We have presented data on two species of coral. In other experiments, we found that ultrasound was also able to detect banding structure in a cylindrical core of *Porites lutea* from Johnston Atoll—the images were similar to that of the Bazaruto coral shown here. The ultrasound system was also used to image flat slab of *Porites porites* from St. Croix but in this case growth bands were not easily detected. The X-ray images of the *Porites porites* sample did not yield a strong banding structure either and, although we have not carried out extensive measurements, it is possible that this species does not have a very pronounced annual density variation.

The ultrasound used here was not able to penetrate more than a few millimetres into the coral. This is consistent with previous reports of very strong acoustic attenuation in coral. It is also consistent with measurements of very strong attenuation in human cancellous bone which possesses a similar structure. The majority of the attenuation can be attributed to

multiple scattering of the ultrasound by the coral skeleton. This multiple scattering will result in a weak but long-lived signal that can, with sufficient signal averaging, be detected by the transducer. This signal may be a way in which to recover information about the coral and deeper locations. Indeed, the data from higher frequency transducers in this study indicated that ultrasound is sensitive to the microstructure of the coral. We speculate that, with proper processing of the signals, ultrasound could be used to recover architectural features of the coral as well as density. These reverberation signals have been used to investigate Aluminum foam which has a similar structure to coral [21]. It is possible that architectural features of the coral may also be used to track growth bands as the change in density is at least partially due to changes in the thickness of the structural elements of the coral. We also note that the use of lower frequency ultrasound would allow deeper penetration into the coral however the concomitant longer wavelengths may not have sufficient spatial resolution to recover the banding structure. This could be addressed by employing spatial correlation techniques which in classical ultrasonic NDE have been successful in recovering the fiber orientation in composite materials [22].

The motivation for these experiments was to investigate the viability of ultrasound as a modality for measuring the annual growth bands within living coral, as the growth bands are indicators of sea-surface temperature. The data presented here indicates that ultrasound has the potential to be an imaging modality for coral structure. Although the preliminary ultrasound images shown here did not have the same fidelity as the X-ray images, ultrasound has a principal advantage in that it can be easily configured as a portable underwater system that can be used in the field. It may therefore be possible to scan coral *in situ*. Although it is unlikely that ultrasound could scan an entire living coral from the outer surface we envision a minimally invasive procedure, requiring that a small hole (diameter less than 5 mm) be drilled into the coral. An ultrasound probe mounted onto a rotating shaft could then be inserted into the hole and measure reflections from the walls of the hole—similar to what is done in intravascular ultrasound [23]. This would allow ultrasound to gain access to the deeper portions of the coral and to measure the growth bands without sacrificing the colony.

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References

1. Draschba, S., Patzold, J., and Wefer, G., 2000, North Atlantic climate variability since AD 1350 in $\delta^{18}\text{O}$ and skeletal density of Bermuda coral: *Int. J. Earth Sci.*, v. 88, p. 733–741.
2. Charles, C.D., Hunter, D.E., and Fairbanks, R.G., 1997, Interaction between the ENSO and the Asian monsoon in a coral record of tropical climate: *Science*, v. 277, no. 5328, p. 925–928.
3. Cole, J.E., Dunbar, R.B., McClanahan, T.R., and Muthiga, N.A., 2000, Tropical Pacific forcing of decadal SST variability in the western Indian Ocean over the past two centuries: *Science*, v. 287, no. 5453, p. 617–619.
4. Cohen, A.L., McCartney, M.S., Smith, S.R., and van Etten, J., 2002, How brain corals record climate: an integration of skeletal structure, growth and chemistry in *Diploria labyrinthiformis* from Bermuda: *Marine Ecol. Prog. Ser.*, submitted.
5. Dunbar, R.B. and Cole, J.E., 1999, Annual records of tropical systems: Pages Workshop Report Series 99-1.
6. Lough, J.M. and Barnes, D.J., 1997, Several centuries of variation in skeletal extension density and calcification in massive *Porites* colonies from the Great Barrier Reef: a proxy for seawater temperature and a background of variability against which to identify unnatural change: *JEMBE*, v. 211, no. 1, p. 29–67.
7. Lough, J.M. and Barnes, D.J., 2000, Environmental controls on growth of the massive coral *Porites*: *JEMBE*, v. 245, p. 225–243.
8. Wellington, G.M. and Glynn, P.W., 1983, Environmental influences on skeletal banding in eastern Pacific (Panama) corals: *Coral reefs*, v. 1, no. 4, p. 215–222.
9. Knutson, D.W., Buddemeier, R.W., and Smith, S.V., 1973, Coral chronometers; seasonal growth bands in reef corals: *Contributions of the Hawaii Institute of Geophysics*, v. 73, no. 72, p. 421–424.
10. Dodge, R.E., Szmant, A.M., Garcia, R., Swart, P.K., Forester, A., and Leder, J.J., 1992, Skeletal structural basis of density banding in the reef coral *Montastrea annularis*: *Proc. 7th ICRS Guam*, v. 1, p. 186–195.
11. ASTM E1001-99a, 1999, Standard practice for detection and evaluation of discontinuities by the immersed pulse-echo ultrasonic method using longitudinal waves, E1001-99a: American Society for Testing and Materials, West Conshohocken, PA.
12. Achenbach, J.D., 2000, Quantitative nondestructive evaluation: *Int. J. Solids Struct.*, v. 37, p. 13–27.
13. Ramsay, P.J. and Cohen, A.L., 1997, Coral paleoclimatology research on the Southeast African Shelf, in Lessios, H.A. and Macintyre, I.G., eds., *Proc. 8th Int. Coral Reef Symp.*, v. 8, p. 1731–1734.
14. Chalker, B., Barnes, D., and Isdale, P., 1985, Calibration of X-ray densitometry for the measurement of coral skeletal density: *Coral Reefs*, v. 4, no. 2, p. 95–100.
15. Hoffmeister, B.K., Whitten, S.A., Kaste, S.C., and Rho, J.Y., 2002, Effect of collagen and mineral content on the high-frequency ultrasonic properties of human cancellous bone: *Ost. Int.*, v. 13, p. 26–32.
16. Pedersen, P.C. and Sun, Y., 2000, Sample impulse response, angular decorrelation and BUA as measures of density and growth axis in coral samples, in Schneider, S.C., Levy, M., and McAvoy, B.R., eds., *Proc. Intl. Sympn.: IEEE Ultrasonics Piscataway, NJ, USA*, v. 2, p. 1329–1332.
17. Faran Jr., J.J., 1951, “Sound scattering by solid cylinders and spheres”: *J. Acoust. Soc. Am.*, v. 23, p. 405–418.
18. Stanton, T.K., 1988, Sound scattering by cylinders of finite length, I. Fluid cylinders: *J. Acoust. Soc. Am.*, v. 83, no. 1, p. 55–63.

19. Evans, J.A. and Tavakoli M.B., 1990, Ultrasonic attenuation and velocity in bone: *Phys. Med. Biol.*, v. 35, p. 1387–1396.
20. Wear, K.A., 2001, Ultrasonic attenuation in human calcaneus from 0.2 to 1.7 MHz: *IEEE Trans. Ultrasonics Ferroelectrics Frequency Control*, v. 48, no. 2, p. 602–608.
21. Lobkis, O.I. and Weaver, R.L., 2001, Mode counts in an aluminum foam: *J. Acoust. Soc. Am.*, v. 109, p. 2636–2641.
22. Derode, A. and Fink, M., 1998, Correlation length of ultrasonic speckle in anisotropic random media: application to coherent echo detection: *J. Acoust. Soc. of Am.*, v. 103, p. 73–82.
23. Di Mario, C., The, S.H.K., Madrestma, S., Suylen, R.J.v., Wilson, R.A., Bom, N., Serruys, P.W., Gussenhoven, E.J., and Roelandt, J.R.T.C., 1992, Detection and characterization of vascular lesions by intravascular ultrasound: an in vitro study correlated with histology: *J. Am. Soc. Echocardiogr.*, v. 5, p. 135–146.