Sonic Imaging
Inspired by Speculation about Dolphins

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Abstract - *Dolphins seem, in effect, to form mental images from a train of temporally isolated, brief clicks. These clicks are strong only in a cone of, roughly,15 degrees, emanating from the dolphin's head. By contrast, humans have developed sound-based tools which create images from a nearly simultaneous set of clicks each of which travels down a cone of, typically, less than 1 degree. We lay a foundation for exploring, through computer-based simulations, possibly practical sonic imaging systems which are similar to those of dolphins and which, using clicks of lower frequency, might "see" through longer distances in water than do existing systems and might also see through sediment.*

1 Introduction to the question

A dolphin emits a brief click forward and, from the resulting echoes, its brain creates, it seems, a 3-dimensional model of the echoing objects. I propose a neural system which could be a basis of such mental modeling. I will then briefly consider how or whether a similarly functioning system can be created using sonar devices and a computer. Imagined applications include a benthic telescope (which might find "the giant squid"), a superior fish-finder, and an imager of human artifacts buried under seafloor-sediments.

Dolphins are born with sonic imaging systems which rely on brief clicks going down a conical path whose angle of opening is about 10 degrees. Existing human methods of "sonar imaging" seem to involve, in effect, scanning a target zone with a pencil of sound, a cone of sound whose angle is less than one tenth that of the dolphin's. Medical "ultrasonic images" and some fine images of underwater objects are created by scanning with a thin beam. Other things being equal, the thinner the beam, the higher the frequency. Frequencies used are, in many devices, above a million cycles per second. Limitations in underwater applications seem to include 1) shorter ranges due to the fact that attenuation of signal increases with frequency, and 2) shorter ranges due to overlap, at longer ranges, of beams which are conically spreading, and which are necessarily simultaneous.

For a single ping of relatively low frequency, range is less limited due to attenuation and there is no other beam with which to overlap and cause ambiguity in the receiver.

Some, possibly all, cetaceans use broad-beam pulses. Given the frugality of Nature, it seems likely that sperm whales use their big heads to "see" food there before diving to a depth of more than 3000 feet. In this line of thought we reach the expectation that the deeper-diving a cetacean is, the more energy is in its ping of sonic imaging, or the larger and more responsive to faint echoes is its sound-collecting system. Relevant to this thought, sperm whales have both huge "foreheads" and long jaws.

But, how do dolphins and other cetaceans create images from a sequence of single, broad-angled, relatively low frequency pings?

2 A foundation for a solution

Let us assume that there is a set *N* of "modeling neurons" and a one-to-one relation G from *N* to the points of a set which, in traditional notation is G(*N*), but which I will call the Grid. Let us assume the Grid exists, abstractly, in a zone of water in front of the dolphin. Current thinking [1] is that the bulbous forehead of a dolphin is a transmitter of "clicks" and the jaw is a receiver of echoes. We imagine the Grid to be attached rigidly to the face of the dolphin.

For each modeling neuron n in *N*, there is the point G(n) on the Grid. Let us suppose a system such that, for each n of *N*, there is a small region around the point G(n) wherein a loud-enough sound emanating from that region will lead to the firing of neuron n.

Neurons have the property that a "firing" of the neuron progresses from one end (the cell body's end), down various axonal branches, arriving at various synapses at various times. These delays, it seems to me, are crucial to sonar imaging.

I postpone the more realistic problem of 3-dimensions and begin with a simpler problem in 1-dimension. An arc is of one dimension.

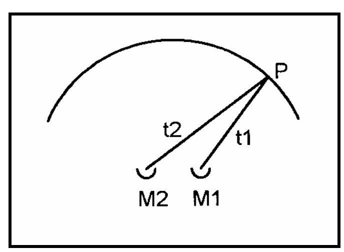

Figure 1. P on arc V.

Let us imagine two "ears" M1 and M2 (we can think of them as microphones), and an arc V so that V, M1 and M2 are all in the same plane (the plane of Figure 1). Suppose P is a point on V and a sound emanates from P. How might a neuron n, such that its point G(n) is near enough to P, fire as a result of that sound; and, so, indicate to the dolphin approximately from where that sound emanated? Our mechanism must also insure that a neuron n that is not "near enough" to P will *not* fire.

Let VG denote the set of all neurons n such that, for some point on the arc V and for a sufficiently loud sound from that point, n will fire. The set VG consists of neurons in our system and V consists of abstract points in space.

We wonder: for points P of the Grid near enough to V, can we determine, via times of transit to M1 and to M2, when a sensed, isolated sound emanates from P? Consider a tiny object at the point P of V and a brief sound, call it Click, coming from, perhaps reflected from, that object at some instant τ. Given the distances indicated in Figure 1, and measuring time from the instant τ when Click leaves P, we see that the time t1, at which Click arrives at M1 is less than the time t2 at which Click arrives at M2.

The ditoa, difference in time of arrival, which is t2 ! t1 uniquely determines, in a perfect and abstract world, some point on the arc V (that point is in the intersection of the arc V and a particular hyperbola). We postpone the problem of the real world not being perfect.

Let us assume that, for some neurons n (perhaps more than one), there is a path, partly mechanical and partly neuronal, from M1 to n, and a shorter path from M2 to n, as in Figure 2. Leaving M1 and M2, Click is transformed into an internal signal Click(1,n) which reaches n from M1 after lapse s1, and also into Click(2,n) which reaches n along the shorter path from M2 after lapse s2. Physical details of the mechanical-neuronal path from an "ear" to n need not concern us here. Probably each such path has neurons and also physical conductors of sound (e.g. the sequence of bones which joins an eardrum to a cochlea's oval window).

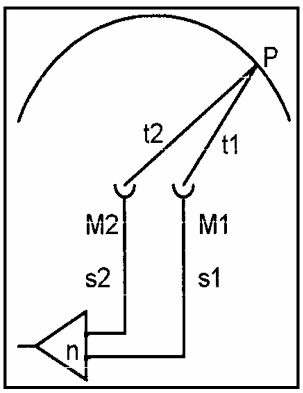

Figure 2. ditoa . 0
t1 + s1 . t2 + s2

Let us assume that if t1 + s1 is near-enough in time to t2 + s2 then neuron n fires and this results, we can say, in a mental picture of a point being at position G(n), near to P, in front of our dolphin, or our (if we choose to so imagine) robotic dolphinoid. At each other neuron nℕ, the ditoa, the difference between t1 + s1ℕ and t2 + s2ℕ, might or might not be nearly enough the same to result in nℕ firing.

This process of detection of nearly-enough coincidental signals at a modeling neuron n is duplicated, one might suspect, in millions of neurons, working in parallel. The natures of these various signals are not important to us, yet. But, let us assume that the click and its input signals to modeling neurons are brief-enough. Dolphins provide an example. From figures in [1] (for examples, see pages 60 and 102), it seems sufficiently accurate to think of the imaging click of a bottlenose dolphin as being two cycles at 100,000 Hertz. I will use just one cycle in my illustrations; though, the very word "cycle" bothers me because it seems to, wrongly, connote periodicy. Let us presume that each of our "points" can produce (contrary to actual points of classical mathematics) an echo which is of sufficient amplitude, at each "ear," to fire a neuron – provided these echoes lead to internal signals which arrive nearly enough together at a neuron.

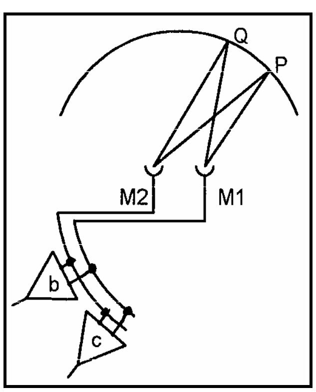

Figure 3. Reflectors
to APs to Neurons.

Assume now that a click is emitted and reflections of this click reach the ears. Imagine just two reflecting dots P and Q on V, as shown in Figure 3, which are near enough to Grid points G(b) and G(c). G(b) and G(c) are not necessarily on V and are not shown, but are near to P and Q respectively.

Presume that the ears (or microphones) M1 and M2 receive signals whose amplitudes, over time, have the appearances indicated in Figure 4.

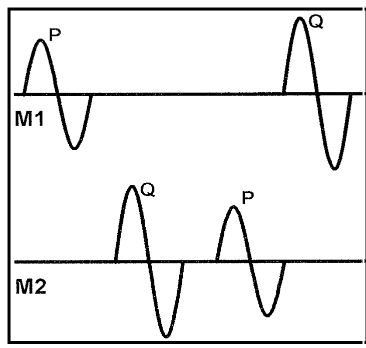

Figure 4. Signals at two APs
over time.

The two signals arriving at neurons b and c might have some version of the appearances indicated in Figure 5. My methods and simulations indicate that the exact shape of the Click is of no great importance. In this example, Figures 4 and 5, neuron b is fired by the echoes from P, and c, by those from Q. At some neuron u the inputs, due to echoes from points P and Q, might be such that the input to u from P's echo and the input to u from Q's echo arrive at nearly enough the same time to fire u. This would generate a "phantom" in the dolphin's mental model and in our sonar image. A phantom is an indication of an object where no object exists. We must elaborate our mechanism to eliminate such phantoms.

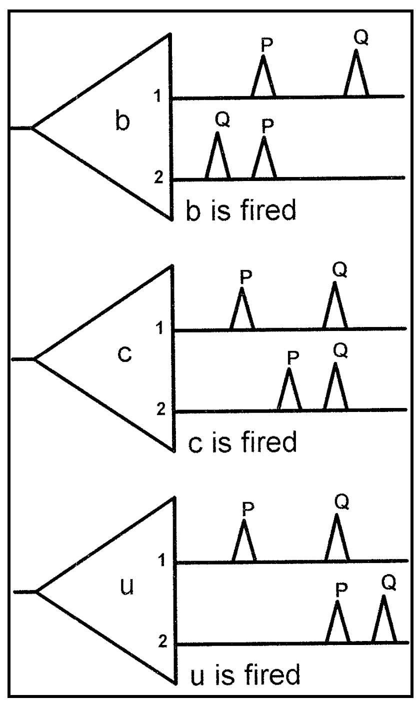

Figure 5. Neurons b, c and u are fired
by P, Q and P&Q, respectively.

The various modeling neurons, indicated only schematically in Figure 3, are such that they fire for sources P “on the right side of the acoustic field.” The length of the signaling path, from an “ear” to a modeling neuron n, is assumed to be such that if a sound emanates at a point P on the Grid near enough to G(n), signals Click(1,n) and Click(2,n) will reach n at nearly enough the same time to cause n to fire. As a hint at possible structure of a brain, we note that if G(n) is on the right side of the acoustic field and n is on the left side of the brain then t1 < t2 and s2 < s1, allowing t1 + s1 to be nearly enough equal to, t2 + s2.

I sometimes will denote by toa(M1,P) and toa(M2,P), the time of arrival at M1 and at M2 respectively, of a sound from a point P.

Let M denote the sequence (M1,M2), and let ditoa(M,P) denote the difference in time of arrival:

toa(M2,P) - toa(M1,P).

For the pictured arc V, we can easily believe that there does not exist another point X of the one-dimensional, smooth arc V such that ditoa(M,X) = ditoa(M,P). But, we shall see that, given more than one reflecting point, there is such ambiguity that we will need more “ears.” If Nature does not seem to provide them then perhaps we are misled by the word “ear” and ought, perhaps, to use some term lacking the connotative baggage of “ear.”

As the arc V moves through the water, the set, or fuzzy set VG of neurons can, by selective firings of those neurons, represent tiny objects which V encounters. For the moment, do not concern yourself with the source of the sounds which result in the firing of neurons in VG. The echoes might be of our dolphin’s click but they could be from a click from a second dolphin (or second sperm whale, etc) swimming in parallel with ours, or from some entirely different source.

Let us now extend our view from arc V into the plane which contains that one-dimensional arc. Again, suppose n is a modeling neuron and a sound emanates from a point P near-enough to G(n). The pair M of “ears” and the number ditoa(M,P) determine a curve or a surface in 2 or 3 dimensions. The shape of this figure is indicated by the word “hyperbolic.”

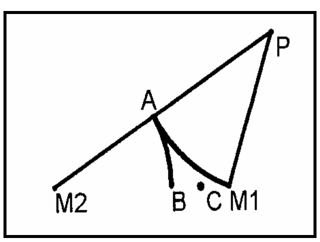

Figure 6. ditoa(M,C)=ditoa(M,P)

Consider Figure 6, where we begin to construct an hyperbola of points of equal ditoa.

Let s denote the speed of sound.

Let A denote the point between P and M2 such that distance(P,A) = distance(P,M1).

Let B denote the point between M2 and M1 such that distance(M2,B) = distance(M2,A).

Let C denote the midpoint of the interval from B to M1.

Let d denote ditoa(M,P).

As an exercise, convince yourself that

d = distance(A,M2)/s and also that,

d = ditoa(M,C) .

Let H(M,d) denote the set of all points X such that d = ditoa(M,X); so that, H(M,d) contains both P and C.

One can show that H(M,d) is the set of all points X such that distance(X,M2) - distance(X,M1) = sd. Remembering Analytic Geometry, one can understand that H(M,d) is an hyperbola (or, some say, one component of an hyperbola). You can see the curve in 2-space and might as well, since you are at it, imagine the surface in 3 space. This curve is half of an hyperbola and the surface, we will say, is part of an hyperbolic surface.

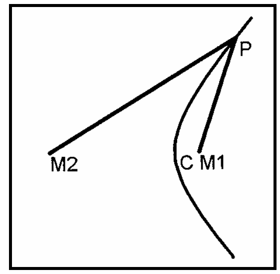

Figure 7. Loci of Points.

For now, we will not assume our system “knows” the time a click was emitted from the dolphin, or some other dolphin, and which resulted in the echoes we study. If we did, we could study elliptical objects which are not, for our present purposes, much different from the hyperbolic.

We are here: a sound emanates or reflects from a point P near Grid point G(n) and this results in the number ditoa(M,P). Our dolphin-brain can figure that the sound emanated from some point on or near the hyperbolic curve or surface H(M, ditoa(M,P)) but cannot, from just one click and two “ears,” pin the source down to Grid’s point G(n). To find the source of an echo, we will need, restricting ourselves to the simple kinds of elements we are using, more than two “ears” even for the 2-dimensional case.

Animals, ordinarily, do not have more than two “ears.” To escape the mental trap created by that word, I will now switch to “acoustic pickup” or “AP.” Some who study dolphins [1] give evidence which suggests, to me, that a dolphin’s lower jaw contains, on each side, a series of acoustic pickups (e.g. possibly, this is just a guess, one for each tooth-socket). This leads to the question: how does timing information in signals from a multitude of acoustic pickups pass through one cochlea? (or, is there another pathway into the brain?) I will not try to solve this biological transducer problem here - but do suggest that the length of the jaw might serve two functions: 1) spatial distribution of acoustic pickups, improving “triangulation,” and 2) distribution, in time, of signals reaching the cochlea, so they do not overlap and destroy each other there.

To illustrate the problem of phantoms, and why more pairs of acoustic pickups seem to be needed, we will consider pairs of APs in a 2-dimensional model. Consider just two pairs M1 = (M11,M12) and M2 = (M21,M22) of APs. Note that “M1" now denotes, not an acoustic pickup, but a pair of acoustic pickups. To more simply illustrate phantoms, we will consider, for each of M1 and M2, just 2 of the 6 surfaces available for the right side of the acoustic field (to the right-front of our dolphin).

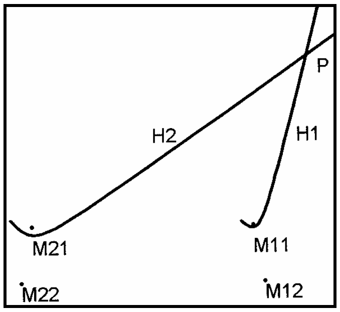

Figure 8. One echoer, no ambiguity.

Figures 8 and 9 are shortened vertically. I presume you can, if you wish, mentally expand the picture vertically by a factor of 20 or so. Suppose P is a reflecting point and d1 and d2 are ditoa(M1,P) and ditoa(M2,P). We have curves:
H1 = H(M1,d1) and H2 = H(M2,d2). Note again that M2 consists of the APs M21 and M22 on the left side of the Figure 8.
H1 and H2 have a common point P, as in Figure 8.

But, if we also have a second reflecting point Q, we also have:
H3 = H(M1,d3) and H4 = H(M2,d4) where
d3 = ditoa(M1,Q) and d4 = ditoa(M2,Q).

There can exist four points H11H2, H11H4, H31H2, and H31H4 at which two of the curves intersect, as in Figure 9 Just two of these four points are real. Given two reflecting dots, we can have two phantoms. P and Q can be the highest and lowest of the 4 points of intersection or they might be the leftmost and the rightmost.

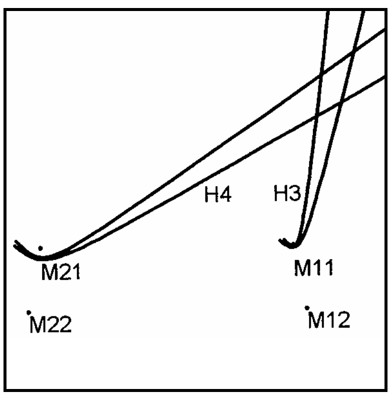

Figure 9. Two real echoers, two phantoms.

More completely, if you examine Figure 8, you ought to see that I have omitted a phantom which exists in even that simplest of cases. And, in a more complete version of Figure 9, I could have indicated 4 more phantoms.

If the geometry of our example is extended to 3-Space then, instead of those 4 (or 8) ambiguous points in a plane, we get 4 (or 8) ambiguous curves at right angles to that plane; each of those ambiguous points in that plane is the intersection, in 3-Space, of that plane and one of those curves. If, instead of just 2 tiny, reflecting objects, we have 3 then we will, in our 2-space simplification, see many more points of intersection of which most are phantoms. Unchecked, proliferation of phantoms would ruin our enterprise. To reduce this problem of phantoms, we can use more pairs of APs.

Given the same number, 4 , of APs, there are six such pairs and their six hyperbolas intersect at P, as seen in Figure 10. We could have each modeling neuron n require nearly simultaneous arrival of Click(K,n) for K = 1 to 4. You might now suspect that 4 is a sufficient number of APs to eliminate phantoms. Alas, the software developed so far seems to demand more.

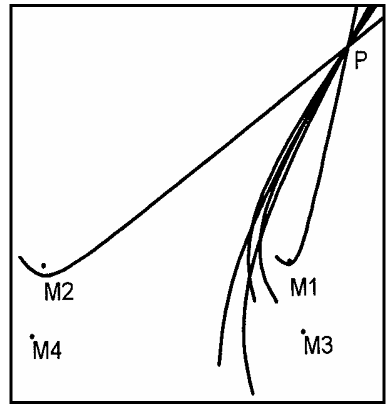

Figure 10.
6 hyperbolae from 4 APs.

As we saw, when objects reflect sounds from some region R of the insonified zone in front of our dolphin, modeling neurons n in the set RG "fire" and this somehow gives the dolphin a model or a view of that object. When we consider the number of neurons needed by a system such as indicated here, we can anticipate some difficulties. Consider the size of the Grid. If the insonified zone is a cone with angle of about 15 degrees and axial height of about 200 feet and if the Grid contains about one point per cubic inch then the number of Grid points will exceed 100 million. And for each point in Grid, we said there is a grid-neuron; and, 4 or more paths, through APs, from point to neuron. Does the system seem too large for us to model for practical, speedy applications?

But we know that animals "focus." So, we can conceive of Nature making, a system of neurons which concentrates, at various times, on various ranges or even on various angles, thereby reducing the size of the system. I have found other simplifying methods as well.

Perhaps someday someone will devise hardware on which to parallelize, practically, some of these operations. In the meantime, using a serial computer, I have found and implemented serial versions of these ideas and have achieved crude images (3D models, actually), of simulated echoing objects, in nearly practical times of computation. I will not here divulge my methods, but will describe results which are typical of many of the various settings of the controlling parameters.

The target consists of one or two simulated fish-like objects which are insonified from above. Each fish has a dorsal fin and a tail. The length of a fish ranges, over various experiments, from about 12 inches to about 20 inches. A fish consists of four to five thousand points, each of which reflects, in simulation, the sonar's click. Echoes at various acoustic pickups are summations of the thousands of individual echoes from points on the fish. The water is assumed to offer no complications such as thermal bending. The computed picture consists of colored dots. The number of dots, so far, is not sufficient, nor are they sufficiently and reliably near to the fish, to produce a likeness of a visual picture of a fish. However, as the fish moves, its tail can usually be detected, swinging from side to side. The dorsal fin sometimes shows up. The patterns of color and motion suggest that, in actual use, species of fish might be distinguished. Two fish, a foot apart, at a range of one hundred feet, show up as two, obviously distinct sets of dots. This might seem remarkable if you consider that the echoes from the various parts of the two fish arrive at different acoustic pickups in different orders and often destructively overlap each other.

Since each dot in the picture must be computed, the number of dots is limited by the available computational power. My first intent has been to work towards a superior "fish-finder," and, so, I have usually constrained my simulations to ones which might be realized with just the computing power of a desktop, personal computer, as they might exist in a few years. More computing power and more expensive sensors could, I suspect lead to pictures having more detail. The computer in the system will allow us to improve each image, in a rapid temporal train, by comparison, before display, with neighboring images.

3 Conclusion

Methods have been simulated for producing 3D models, and hence images, from reflections of a single, brief, wide angle sonar click. The images are, so far, crude but serviceable for finding fish, possibly for identifying species of game-fish. There seems to be no inherent reason that the system cannot be scaled up to be used as a sonic telescope on targets at a range of thousands of feet, assuming a sufficiently simple medium in which sound travels.

The system can be scaled down, as well as up, in size. So, one might begin to imagine applications such as a hand-held device for rapidly detecting shrapnel in wounds on a busy battlefield.

I expect that the single-beam methods indicated here will work for radar – allowing, for example, a dispersed, multi-array system to better discriminate an approaching warhead from its accompanying decoys.

Potential aquatic applications seem to include 1) the world's best fish-finder, 2) the first benthic telescope (for seeking, for example, "the giant squid"), and 3) an imager of the wooden ships which have sunk to and, over eons, been chemically preserved under sediments on the bottom of the Black Sea.

All of these dreams remain contingent upon at least a first physical implementation of the system.

Reference

[1] Whitlow W. L. Au, *The Sonar of Dolphins*, 1993, New York: Springer-Verlag.