Acoustic Modems, Navigation Aids, and Networks for Undersea Operations

Dale Green
Chief Scientist
Teledyne-Benthos, Inc.
49 Edgerton Dr.
North Falmouth, MA 02556
508-563-1000

Abstract – **At present, the realities of acoustic communications and undersea networks differ substantially from the expectations arising from academic theory and investigation. The issue is not that the fundamentals of communications theory do not apply, but rather the fact that the difficulties of the acoustic channel do not necessarily fit the assumptions underlying conventional applications of that theory. In this paper we describe many of the practical problems that have been addressed over the past twelve years of modem development. Some of the issues addressed have an RF analog, but the severity of the channel and the combination of channel constraints and modem-platform operations makes acoustic communications a very different problem. In particular, we address these issues via their impact on physically small, battery powered, DSP-based, omni-directional modems. We describe recent developments in modem-based navigation aids and sensors. Finally we describe progress toward using commercial acoustic modems as the basis for underwater networks. We discuss design choices at the physical, link, and network layers that are consistent with the compound constraints of the transmission channel and modem.**

I. INTRODUCTION

Underwater acoustic communications (acomms) is an emerging technology that today provides useful and effective methods for transferring information underwater. There are clearly identified commercial applications for acomms, especially within the oil and gas industries. Environmental monitoring with remote sensors is yet another important application. As an example, the tsunami warning sytems that have been deployed in many parts of the Pacific, Indian, and Atlantic oceans use acomms to transfer sea floor measurements to a surface (gateway) expression. There is a large and growing requirement for acomms on unmanned underwater vehicles (UUVs), and undersea distributed sensor systems must rely on acomms networks.

There is still considerable research underway at the academic level, especially with regards to physical layer methods (e.g., waveform acquisition and modulation schemes), and the development of reliable undersea networks. Nontheless, reliable and moderately-priced acomms modems are available from several commercial sources. Some emphasize low power consumption, while others provide high data rate links without regard to energy consumption. Some relay on spatial directivity or redundancy, while others use simple single-channel transducers. There are few, if any, standards, and performance is extremely sensitive to channel conditions, geometry, and application.

This paper first discusses in a general sense the impediments to acoustic communications (acomms). We then describe the characteristics of the Teledyne Benthos Telesonar modems. This description covers modulation techniques and a discussion of the most difficult part of acomms – the detection of the signal and the temporal and spectral alignment required for effective communications. Next we discuss several novel modem-based systems that provide capabilities beyond underwater communications, and finally we provide an overview of Seaweb, the US Navy's undersea networking program.

II. IMPEDIMENTS TO UNDERWATER COMMUNICATIONS

The primary function of modems is to both transmit and receive signals that represent digital data—binary ones and zeros—over what usually is a hard-wired link such as a telephone line or a microwave link. In fact, the word modem is derived from the terms modulation and demodulation, which refer to the coding and transmission, and the receiving and decoding of digital data, respectively. Two key factors measure a modem's performance: speed and reliability. Speed is measured by determining the number of information bits transmitted per second, which is referred to as the bit rate. Reliability is measured by determining the bit error rate, which is the ratio of the number of bits received in error to the total number of bits transmitted.

Except when noise interference is high, modems that transmit and receive data over phone lines or microwave links typically function nearly error free, and at baud rates of 128,000 bps or more. In addition, repeater systems allow virtually unlimited transmission ranges. Those same performance factors are also used to measure the capabilities of the undersea modems. However, with the transmission medium being water and the transmitted signals being sound, a number of physical barriers exist that constrain those performance factors, physical barriers that are not present in either wire or microwave links.

The major factors that constrain the performance of any communications system that uses water as a communications medium are the relatively slow speed of sound in water, the signal fading characteristics due to sound absorption and destructive interference, the multipath interference due to sea surface and sea floor reflections, and reflections from nearby objects.

The speed of sound in seawater, on average, is about 1500 meters/sec. This is compared to electromagnetic signals that

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travel at nearly the speed of light. However, the relatively slow speed of sound in seawater has no direct effect on the baud rate of the modems; it affects only the latency between the transmission of a signal and its reception. In most applications, this delay is not of much concern, as the alternative is to use a hard wired connection, which is sometimes prohibitively expensive or not feasible.

Signal fading is primarily caused by spreading loss and the absorption of sound in water, but it is also caused by destructive interference due to multipath, a situation where signals of like frequency nearly cancel each other. This frequency-dependent fading occurs when a multipath-induced reflection of the transmitted signal arrives at the receiving transducer at the same time as a transmitted signal of the same frequency. The result is a reduction in the amplitude of both signals. Signal fading due to spreading loss is a result of the dispersion of energy as it radiates outwardly from the transmitting transducer. And signal fading due to the absorption of sound in water increases with increasing frequency. To a lesser extent, environmental factors such as temperature, pressure, and salinity also affect absorption, and absorption also occurs at the sea floor.

Multipath is the factor that most restricts both the bit rate and the reliability of an acoustic modem. Multipath, which is particularly severe when attempting to communicate over the horizontal channel in shallow water, is the result of sea-surface and sea-floor reflections, reflections from objects that are near the receiving modem, and refractions from thermal gradients and water turbulence. Using directional remote transducers reduces the effects of multipath when the transducers are aimed at each other, yet reflections from objects such as piers or boats that are near the receiving transducer cause overlapping of the received signals, resulting in decreased reliability. In addition, multipath is usually not stationary; hence even techniques used to track and reduce the effects of multipath do not significantly improve modem performance in increasingly dynamic multipath situations. As a result, multipath forces continual trade-offs in the speed, the reliability, and the cost of acoustic modems.

III. TYPICAL MODULATION METHODS

We next describe three common modulation schemes, each of which support different applications and provide different capabilities. All such schemes provide a transition to placing energy into the channel from a common path of data preparation. That path includes forward errorcorrection coding (ECC) and symbol interleaving. The modulations all support standard base-2 Galois field arithmetic, with alphabet sizes of M = {2,4,8, etc.} [1]. We provide a brief overview of each modulation scheme in the following sections.

III A Frequency Hopping

Frequency Hopping (FH) involves the placement of short continuous wave (CW) tonals at specific locations in frequency as time passes. Generally, we consider the placement of only one tone at one time, although this is not a fundamental requirement. Each tone conveys approximately ½ bit of information, with M = 2. Tones are orthogonally-spaced in frequency, and the scheme provides a low data rate, yet highly robust connection. Typical data rates[1] provide approximately 80 bps of (true) data rate. The Telesonar scheme uses a pseudo-random frequency placement for the tones, and it employ a number of similar tonals as a precursor for signal acquisition and alignment.

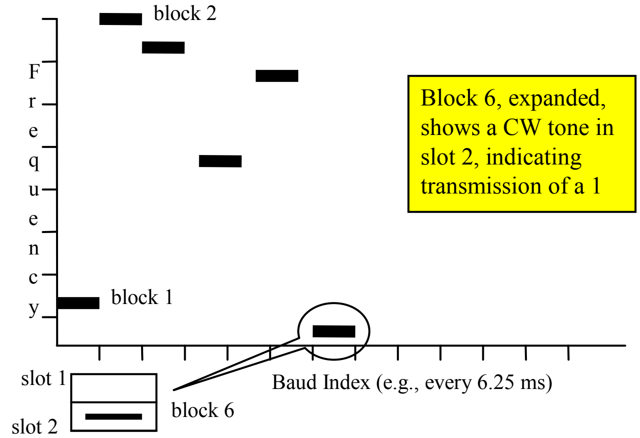

Figure 2. Example of Frequency-Hopped Binary FSK.

There are three primary advantages to this form of waveform: the scheme is very tolerant of exceedingly long multipath; it is very good for low Signal-to-Noise Ratio (SNR) applications; and it can be made tolerant of the simultaneous presence of similar waveforms from multiple sources. That is, this can be considered a Code Division Multiple Access (CDMA) technique. There are also three drawbacks: the scheme is only tolerant of range rate (relative velocity) consistent with the inverse of the tonal duration; the range resolution is approximately limited by the tonal duration; and the data rate is quite low (80 bps in our case). Figure 2 shows a simple example in the time-frequency plane where M = 2 (binary).

III B Multi-Channel M-ary FSK

The term multi-channel M-ary FSK is not properly descriptive, but it has become the standard term used to describe the principal modulation method used in the Telesonar modem. In this scheme we simultaneously transmit 32 tones spanning a 5120-Hz bandwidth. Two of the outer tones are used for Doppler tracking, while the remainder carry information. Each information tone may be placed in any of four adjacent frequency slots, which together form a block (there are thus 30 blocks). The selection of the slot is decided by the M=4 alphabet. At a data rate of 2400 bps, we transmit raw data without recourse to ECC or any other form of 'protection." At 1200 bps, we add ECC. For more reduced rates, we add various forms of redundancy and/or temporal separation of the tones. Available data rates range from 140 bps to 2400 bps. Figure 3 provides an example of this method.

[1] Similar methods are used in the WHOI Micromodem and the Telesonar ATM

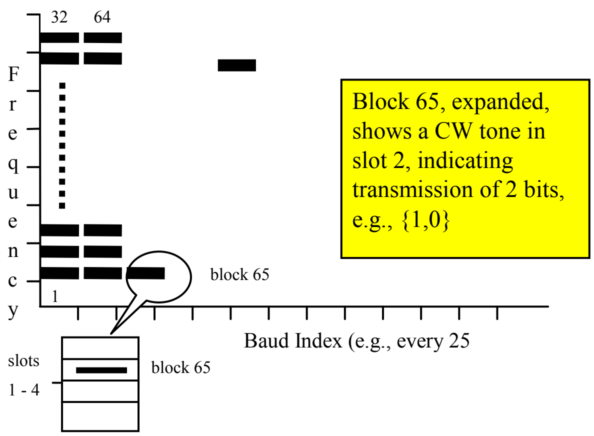

Figure 3. Example M=4 MFSK scheme transmitting 2 symbols with each tone.

Unlike the FH method, for this scheme we use several precursor waveforms for acquisition and alignment. In particular, this includes a patented method which permits these small, battery-powered devices to communicate with high-speed platforms. However, this method is ill-suited for multi-access applications.

III C M-ary PSK

This scheme supports communications at data rates from 2560 bps to approximately 15 kbps, although the latter is suitable only for ideal channels. Here we encode symbols via the use of extremely short tonals, all at the same frequency, with the phase of each tonal conveying the desired information. The success of this technique depends on the robustness of the Decision Feedback Equalizer (DFE) which resides at the receiver and which attempts to invert the propagation channel, as defined by its impulse response. In essence, the inversion process attempts to coherently combine all multipath into a single equivalent path. The performance of the DFE in turn is dependent on the statistical stationarity of the channel and the capability of the processor to handle the requisite number of feedforward and feedback equalizer taps (within the time defined by the tonal duration). The current implementation of the equalizer in the Telesonar modem handles approximately 2-3 ms of multipath, and thus is best suited for vertical channels.

III D Signal Acquisition and Alignment

Acomms typically operates on the assumption that the arrival time of the signal is a completely unpredictable event. Therefore, it is necessary to incorporate a mechanism that can detect the arrival. It is also necessary to ascertain the precise start of the modulated message and to estimate the influences of channel spreading and platform range rate. It may also be desirable to estimate the spreading characteristics of the channel, as well as the SNR for the received signal. In the Telesonar modem these are done nearly simultaneously.

With any wireless communications system provisions must be made to accommodate rapid relative velocity among users of the system. This is especially true of underwater communications, which have limited bandwidth and otherwise difficult channels. All communications signals contain components used for acquisition and alignment, where, in the broadest sense, alignment pertains to both the temporal and spectral identification of the modulated portion of the larger signal. A typical signal component is a linear period modulated (LFM) waveform. This is processed with a "matched filter" using as a filter an exact replica of the transmitted LFM. The peak of the filtered output indicates the arrival time of the signal. When relative velocity (i.e., range rate) occurs, the waveform is distorted by temporal compression or dilation, which has the affect of also compressing/dilating the spectral content of the waveform. In this case the basic filter is no longer a good "match" for the received signal. The distortion causes a decrease in the peak filtered response, as well as loss of precision in estimation of temporal alignment. Furthermore, nothing is revealed about the spectral distortion of the signal. The desire here is to substitute an acquisition/synchronization subsystem which can provide acquisition of a packet and provide satisfactory alignment with the modulated message over a wide span of range rates. At the same time the acquisition must provide initial estimation of the range rate so the remainder of the signal can be corrected to enable the demodulation to proceed as if there were no motion present.

The classic method for solving this problem is to form a multi-hypothesis, maximum likelihood estimator, wherein a "bank" of filters are formed, each reflecting a different hypothesis of range rate. The number of filters used must account for the degree of spectral distortion imposed by the motion. Typically, a new filter must be used when the adjacent filter peak is reduced by 50%. The system then observes all of the filtered outputs and chooses that one with the largest peak. This "best" choice of filter then determines the range rate, which observation can be used to correct the remainder of the signal for the imposed spectral distortion.

The approach just described is considered optimal under typical conditions of an additive white Gaussian noise channel. However, the computational burden is very high, and, as in our case, may be prohibitive for a small, battery-powered digital signal processor (DSP). We have developed an alternative acquisition signal, which is robust in the presence of range rate, and which is composed of a primary and secondary pair of waveforms, to identify the range rate. The combination of the two is used for purposes of both temporal and spectral alignment.

IV. MODEM-BASED SYSTEMS

Even though there is considerable academic research underway in underwater communications, modems *per se* are rapidly becoming commodity items. Low data rate modems (in the hundreds of bits per second, or BPS) are quite suitable for many, if not most applications. Such applications typically gather limited amounts of information over a period of time, then "burst" it between modems. Command and control of undersea assets usually does not require high data rates. Moderately high data rate systems (in the few kBPS) are also available, although they typically require more demanding processing infrastructure, or much higher SNR, or both. Very high data rates (multiple kbps) systems are available at research institutions and for highly specialized, very short range applications, such as video telemetry.

There is growing interest in undersea systems which integrally combine a robust acomms capability with some other activity which can share the resources of the modem. In the following, we describe three such systems, each of which have at minimum advanced beyond the prototype stage.

IV A Modem-Based Sensing

A communications system must have data to transmit. The data may be nothing more than a "heartbeat" of a sensor system to let a remote entity know that it is functional, or it might be a video stream sent back from an underwater vehicle. Without data, a communications system serves little value. Historically, modems have been attached to offboard sensor systems – such as temperature and salinity profilers, or current monitors. Today we introduce a new concept, the MBS 100, which is an extension of our popular SM 75. The SM 75 contains or provides the following:

- A 17-inch or 13-inch glass sphere, rated to 6000 meters, or full ocean depth, respectively
- A fully functional Telesonar modem with transducer
- A modem-controlled burn-wire release
- Inherent buoyancy
- Data logger for attached sensors
- Batteries
- Deployment and recovery by two people operating from a small craft.

The MBS 100 specifically adds the ability to process one-or-more channels of analog signal or digital data– for purposes defined by the software resident in the signal processing infrastructure. The source of these data may be the modem transducer used in parallel as a hydrophone, it may an auxiliary hydrophone, or it may be non-acoustic in nature. Furthermore, we have added an extremely low-power mass storage device (currently up to 64 Gbyte, soon to be at least 128 Gbyte) which may be used to record either raw, semi-processed, or processed data. We note that, in addition to the mass storage, the modem-based "data logger" can accept data via an RS232 line (e.g., from the signal processing board) and have it available for acoustic upload.

The signal processing DSP is provided with a variety of standard dsp-related tools, such as band selection, basebanding, FFTs, matched filter algorithms, image compression algorithms, lofargrams, etc. Figure 1 shows two views of the assembly. In this configuration, the modem operates at a high frequency (our standard 22 to 27 kHz band), while analyses and storage may be done on any subband up to 30 kHz.We are prepared to work with our customers to implement the specific processing algorithms required for their applications.[2]

We wish to note one particular application already underway. There is an imperative within the US (and elsewhere) to monitor and protect marine mammals. This system is in use as a low-cost recording device specifically for right whales. Our future plans are to embed the requisite detection and classification algorithms specific to this animal within the *in situ* signal processing architecture.

[2] We note that some applications may be ITAR-controlled.

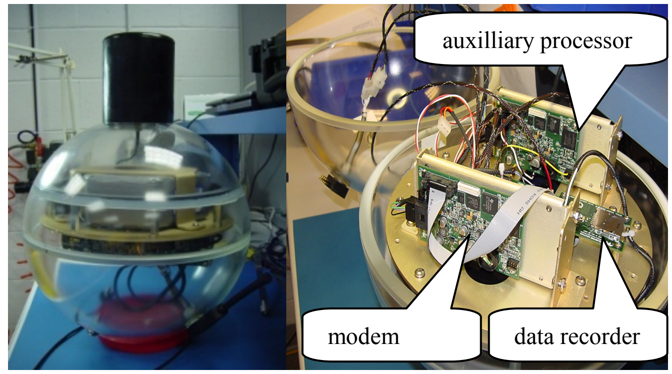

Figure 1. Fully assembled MBS 100 and an open view of the electronics

IV B Navigation Aids

The Directional Acoustic Transponder (DPC) is an extension to the Teledyne Benthos Telesonar modem which automatically estimates the azimuthal and vertical arrival angles of a message sent by a remote modem. The system is a "modified" ultra-short baseline (USBL), which, unlike most competitive systems, uses a broadband component of a typical modem message to form estimates of arrival angle(s). While conventional USBL devices employ tonal signals, the appropriate processing of wide band signals provides far better combined range and arrival angle estimation, especially at low SNR. The device offers a clear 360 degree field of view in azimuth, and an approximate vertical coverage spanning 140 degrees (from vertical). At modest SNRs our azimuthal bearing accuracy is approximately ± 1 degree and the vertical accuracy is approximately ± 2 degrees.

Range between two modems is obtained via 2-way messaging. 2-way accuracy is approximately 0.5 meters at all ranges, neglecting propagation effects (e.g., refraction). If a remote modem queries a DPC with a range command, the DPC responds with a message containing the received angles. The requesting modem estimates range based on the turn-around time. The DPC may also return its own geo-location, which then is sufficient information for the remote modem to estimate its own position.

We can place the DPC on a moving platform as we have integrated an extremely small, low power 3-D rotational motion detection package, with compass.

We emphasize that the DPC is an adjunct to a standard 4th generation Telesonar modem. As such, a user has full access to our entire suite of underwater communications capabilities. The DPC in no way compromises any communications function – it simply estimates the angles of arrival for every Telesonar message addressed to it, and passes the information on to its host. If the modem/DPC receives a range request from a remote modem, it automatically responds with the estimated angles.

The DPC requires a hydrophone assembly separate from the modem transducer, although the two may be "potted" together as a vertical stack, as shown in the following figure. The two may also be physically separated, generally a more suitable configuration for a UUV.

Figure 2 shows, in the lower picture, one type of PCB board layout including the required attached multi-channel signal conditioning board. (Both the standard modem (upper right) and the smaller Compact Modem (left) are also shown). The multi-channel board may be physically separated and connected via ribbon cable, as shown, or it may be stacked. A combined hydrophone/transducer stack is shown in Figure 3, along with the required electronics. The modem board set alone is approximately 135x76x72 (mm). When fully awake (receive mode), the combined unit consumes approximately 0.6 W. Figure 4 – 6 show various present-day DPC applications.

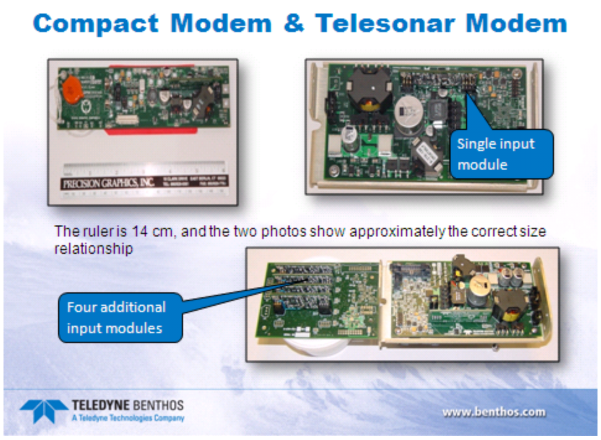

Figure 2. Photographs of various DPC and other modem components

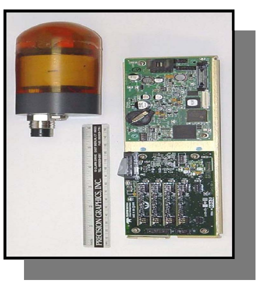

Figure 3. All modem components, including wet-end.

Figure 4. Navigation aid for many varieties of underwater platform

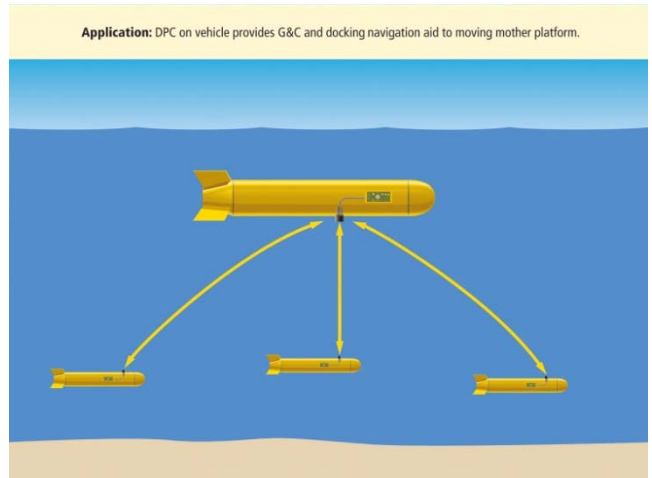

Figure 5. Guiding and docking multiple UUV

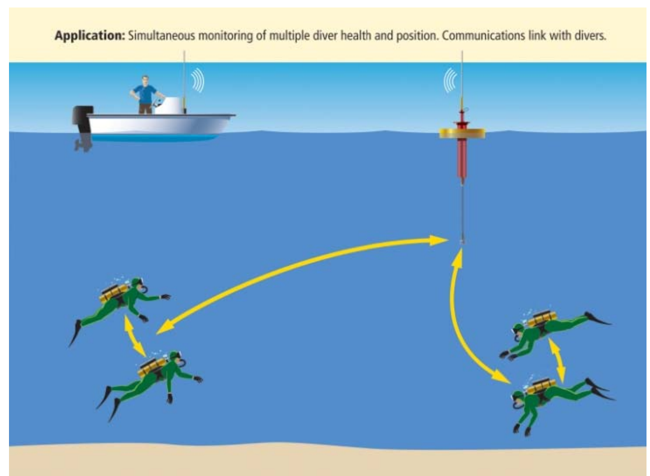

Figure 6. Diver Tracking

IV C Undersea Networks

In this section we discuss undersea networks as represented by Seaweb, a 12-year combined modem and networking development by Teledyne Benthos and the US Navy. A more thorough discussion of Seaweb is provided in a recent MAST paper [1].

Seaweb is implemented as Navy-restricted firmware operating on Benthos commercial modem hardware [2]. The power of Seaweb connectivity was successfully demonstrated during recent experiments depicted in Figures 7-9. Figure 7 shows a collection of gliders fitted with telesonar modems exercised as mobile nodes in an experiment conducted with DRDC of Canada. These gliders, manufactured by Teledyne Webb Research of Falmouth, Massachusetts, contain GPS, Iridium, FreeWave, and ARGOS in the tail section. Such communications assets, when combined with the onboard acoustic modem, make these AUVs effective mobile gateway nodes without the attendant vulnerability of moored gateways.

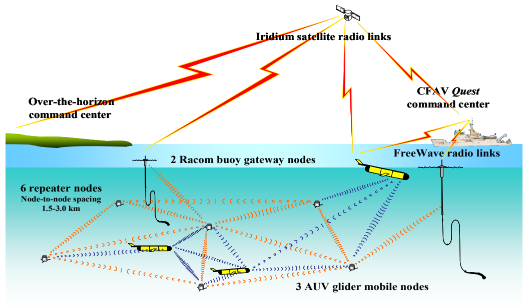

Figure 7. The February 2003 Q272 Seaweb network in the Eastern Gulf of Mexico included three AUVs, six repeater nodes, and two gateway buoys

Two substantial exercises were conducted with the US Navy, as depicted in Figures 8 and 9. In the former, a submarine maneuvered around a 14-node Seaweb network accompanied by two RACOM buoys. This was the first example of email being sent over wireless acoustic links from the submerged submarine to an ashore command center. In the latter, an experiment in 2004 demonstrated the reliability of the Seaweb network as it repeatedly overcame disruption to the pre-planned network caused by two hurricanes and, more significantly, severe trawling. The figure on the left shows the planned deployment, while that on the right shows the reconstructed, and fully functional, network locations at the end of the experiment.

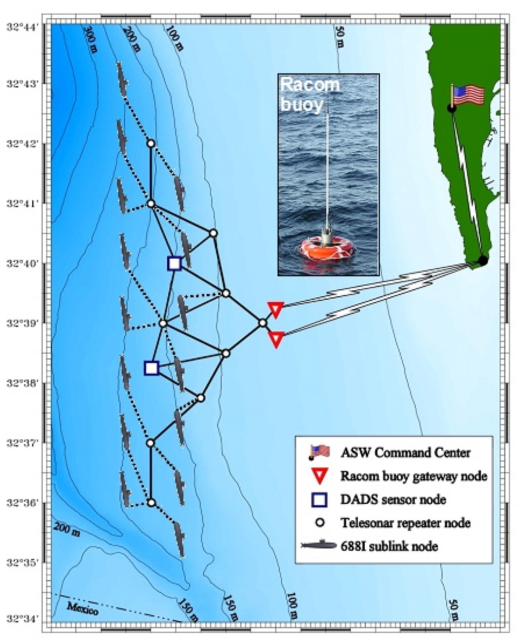

Figure 8. A June 2001 Seaweb network was a 14-node undersea grid installed on the Loma Shelf adjacent to San Diego (left). Mobile positions near the nodes are indicated by the submarine icon.

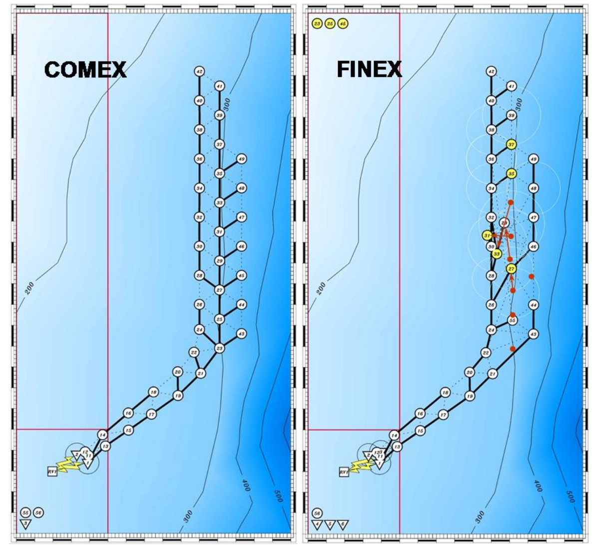

Figure 9. Experiment conducted in 2004 with 40 nodes. Figure on the left shows the planned deployment, while the right hand figure shows the final position following hurricanes and trawling.

Although the specific network implementation called Seaweb is owned by the US Navy, much of its conceptual design is based upon fairly straightforward textbook network concepts. While there are a few details which truly are restricted, Teledyne Benthos has developed an alternative networking scheme in which the "network" protocol has been removed from the modem DSP and transferred to an auxilliary computer, such as a laptop or an embedded daughterboard. This was done specifically to enable (academic) researchers without access to physical modems to experiment with network (and higher) protocols without having to be concerned with the physical and link layers. This implementation is called "BONITO" and is available with all Telesonar modems.

V. ACKNOWLEDGEMENTS

The US Office of Naval Research (ONR) has sponsored the development of Seaweb technology, with significant investments from the US Small Business Innovative Research (SBIR) Program. The National Oceanographic Partnership Program (NOPP), the US Navy Program Executive Office for Integrated Warfare Systems (PEO IWS), the US Navy Program Executive Office for C4I and Space (PEO C4I&S) and the US Navy Program Executive Office for Littoral and Undersea Warfare (PEO LMW) have provided opportunities for experimentation

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VI. REFERENCES

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