Underwater Modem-Based Navigation Aids

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ABSTRACT. Both autonomous and semi-autonomous underwater platforms require navigation capabilities. Acoustics have long been the preferred method, because all other methods are so limited in range and/or are so costly. Traditional methods have relied on tonal-based waveforms used with any of three approaches: long baseline (LBL), short baseline, or ultra-short baseline (USBL). These systems can be highly effective when propagation conditions are "good," but may incur high cost in terms of false and missed detections. The use of wide-band waveforms can substantially improve performance, but a significant cost in incurred in the complexity required at the receiver. However, given this complexity, consideration should be given to the use of underwater acoustic communications (acomms) as the provider of enhanced navigation aids. We describe three modem-based navigation aids based, two of which have never exhibited a false alarm, and each of which provides substantial improvement over tonal-based systems. We describe a spread spectrum signaling method used in LBL navigation, an underwater GPS system in which any number of platforms can obtain accurate geoposition in a completely passive sense, and we describe a physically small, wide-band modification to conventional USBL. All of these systems provide high accuracy navigation while retaining full acomms links.

1 Introduction

Providing navigation and localization of underwater platforms is difficult, often expensive, and highly subject to temporal and spatial non stationary and non-linear channel effects. High value platforms, such as submarines and large unmanned underwater vehicles (UUVs) may carry inertial aids, but these are both very expensive and subject to drift over time. The more common approach, suitable over restricted spatial volumes, is to employ acoustics in one of several ways to obtain some combination of range, azimuthal bearing, and depth. In this paper we briefly describe several traditional methods for obtaining these measurements, then turn to the use of underwater acoustic communications (acomms) as a core technology offering important enhancements to these otherwise well-understood traditional methods.

The primary acoustics-based localization methods we discuss here are so-called long-baseline (LBL) and ultra-short baseline (USBL). A third method, the short baseline (SBL) is somewhat of a mixture of the other two but has severe issues of deployment and utilization relative to the types of systems we will discuss, so little attention is given to this method. A variant on the LBL technique which emulates satellite GPS is described is also described. This method is particularly attractive for situations with multiple underwater platforms (which wish to or must remain silent), provided the LBL sources carry highly accurate and synchronized clocks.

The LBL and USBL techniques traditionally have employed very short tonal signaling methods. These types of signals cause the system to be subject to high false alarm rates as well as to loss of signal energy due to multipath. While the tonals are short, the resolution in time (range) that they offer is rather poor without very high signal to noise ratios (SNR). The use of broadband waveforms, when combined with appropriate signal processing, can substantially improve the performance of these systems.

Most modern underwater acomms systems employ combinations of often complicated waveforms in order to move a message through the difficult acoustic channel. We demonstrate here how acomms technology – and the signal processing infrastructure required to support it – can be used to improve otherwise traditional localization methods.

Chapter two describes LBL and USBL schemes from a traditional point of view. We point out the limitations of tonal signaling in a multipath environment. Chapter two describes several techniques used in the Teledyne Benthos "Telesonar" modem for underwater communications. We also show how simple broadband waveforms can be virtually immune to some of the multipath-induced problems of tonal signals. Chapter three then describes a robust re-implementation of an LBL system using a robust spread spectrum signaling method. We demonstrate how this same approach may be used to build a very robust underwater GPS system. Finally, we describe how we have re-implemented USBL localization using phase-coherent broadband signaling tightly integrated with our core acomms technology. Chapter four provides concluding remarks.

2 Acoustics-Based Localization

LBL and USBL systems fundamentally utilize one signal arriving at multiple receivers with measurable differences in arrival times at those receivers to estimate direction of arrival. This section describes these two techniques.

2.1 LBL

An LBL system is model-based in the sense that we assume spherical spreading from the source to each of the receivers (and back again). For example, the UUV transmits a "ranging command" at time T_{0j}, which is received at at the j^{th} transponder some distance D_j away after an elapsed time delay of T_{Dj}. After a (known) turn-around time τ_j, the transponder returns a signal, which is received back at the UUV after anoth delay of $T_{Dj} + \varepsilon$, where e is a possible offset due to propagation changes or motion. Ignoring the processing time in the UUV, the total travel time is

$$T_j = 2T_{Dj} + \varepsilon + \tau_j \quad (1)$$

Since we assume that we know the turn-around time, the estimated range from the UUV to the transponder is simply

$$R_j = c(2T_{Dj} + \varepsilon)/2 \quad (2)$$

where c is the (assumed constant) speed of sound.

If we have several well-separated transponders, all of which can respond without mutual interference, then we have a problem of overlapping spheres, which has a unique solution. In practice, the solution is contaminated by uncertainties caused by channel conditions, and straightforward geometric solutions are usually ineffective.

Several excellent descriptions of applications and solutions can be found with a Wikipedia search ("long baseline navigation"). Our experience leads us to ignore elegant statistical solutions such as least squares in favor of a simple 2 or 3 dimensional search approach. Simply stated, assuming known locations for the transponders, we obtain the measured ranges to each, and assume that the UUV is at a (start) location in space. We then gradually change the assumed UUV position until we obtain a location whose straight-line distances from the assumed transponders most closely matches the measured ranges. As an example, Figure 1 shows a simple straight-line track through a region bounded by four transponders. The locations of the buoys is marked by fuzzy red circles showing the composite positions with a 10 meter standard deviation error in both latitude and longitude. The range estimates each have a 10 meter standard deviation of error in both latitude and longitude. The true UUV positions are shown by the black "o" mark, while initial position estimates with error are shown by the red "x."

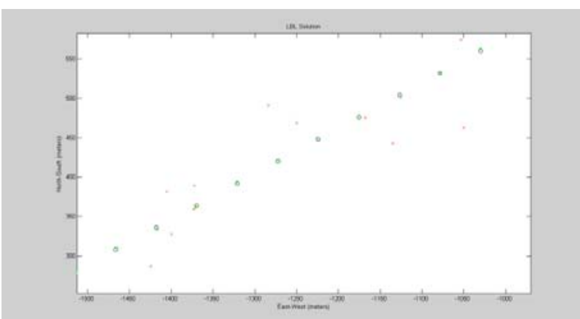

Figure 1. A simple track through a field of 4 transponders.

The final solution is shown by the green "+." A close-up is shown in Figure 2, where we see that the interpolated

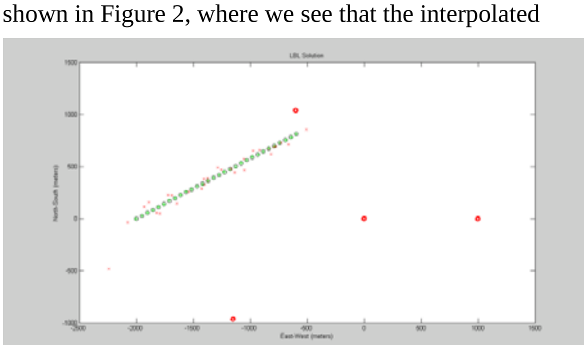

Figure 2. A close-up from Figure 1.

location does an excellent job of truly locating the UUV. We note that application of a least squares solution does not improve on this performance.

2.2 USBL

Whereas LBL processes the differences in arrival times from multiple, spatially-separated transducers, USBL reverses the concept and receives the transmission from a single source on multiple, closely-spaced receiving hydrophones. The hydrophones are spaced not greater than half of a wavelength apart, and time difference is inferred from phase differences among the signals arriving at the hydrophones. Figure 3 shows a very simple representation of a 2-element USBL where a tonal arrives at the two phones with a resulting phase difference. We then infer a time of arrival difference based on a narrow band model.

With only two elements, we have forward and backward, and up and down ambiguity. Multiple elements can resolve these ambiguities. We observe that this is inherently a very narrow-band (tonal) process, but it can be highly accurate with sufficient SNR.

The black circles show true UUV position, the red circles show (randomized) transponder locations, the red plus marks show initial UUV position estimates. See Figure 2 for a close-up.

Figure 3. A simple representation of a tonal USBL navigation aid.

2.3 Narrowband vs. Broadband Signaling

The examples shown do not assume anything about the channel – in the case of LBL, all transponder requests from the UUV are received by all transponders, and responses are always received by the UUV. This is generally not the case given that we are using tonal signaling. Tonal signals typically are used for the following two reasons:

1. The method requires simple electronics and is therefore relatively inexpensive.
2. Using tonals permits multiple units to operate in different, non-overlapping frequency bands, thereby avoiding mutual interference

The most effective method for detecting a known waveform is to build a filter especially crafted to mimic the structure of the waveform as it will exist at the receiver (not necessarily as it existed when transmitted). Unfortunately, it is often impossible to know *a priori* what the ocean channel will do to a waveform, so instead we construct a compromise filter which reflects both its origination and the gross effects of the channel. For a CW ping, this is most appropriately a bandpass filter.

Typical pingers/transponders reflect an inability to (cost effectively) tune electronics to produce a pure CW at a precise frequency. Consider, for example, the tonal pinger used for aircraft “black box” recovery. The design calls for an approximately 10 ms CW ping to be transmitted anywhere within roughly a 2 kHz band (e.g., between 38 and 40 kHz). Unfortunately, this requires a receiver to use a detector operating with a 2 kHz wide bandpass filter. As the actual effective bandwidth of a 10 ms CW ping is only approximately 100 Hz wide, we see that the design imposes a severe mismatch – reflected in a 13 dB loss in signal-to-noise ratio (SNR) which is self-imposed by this poor design.

Waveforms traveling over different paths typically arrive at a particular point in space with differences in both arrival time and possibly phase shifts as well (for a CW waveform the two are generally indistinguishable). Such overlap can either enhance or degrade the resulting waveform, as described next. Figure 4 shows two figures side-by-side, each with two plots. The upper plot shows the time history of the ping (plus noise), while the lower plot shows the output of a (spectrally wide) bandpass filter. In both figures the same CW signal arrives over just two paths, but with very subtle differences in arrival time shown between the left and right arrivals. The SNR in both cases is quite high.

The conclusions to be drawn with this type of pinger/transducer design is that a high frequency CW waveform will suffer from excessive attenuation, may suffer from multipath interference, and will likely be lost in noise because of the wide filter.

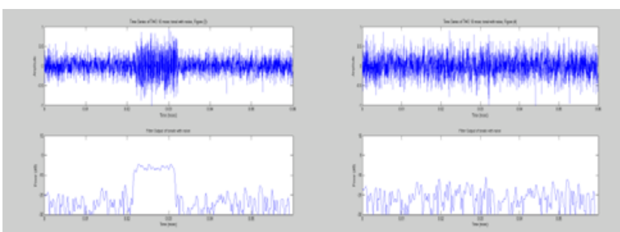

Figure 4. Two examples of a CW signal in noise arriving over two paths. On the left, the signal is apparent, on the right, with subtly different arrival times, it disappears.

Broadband Signaling

Signals occupying a bandwidth considerably wider than the inverse of their duration (a measure of a “CW” waveform) are considered to be broadband, and offer considerable advantage over the older technology. First, they are far less likely to disappear with multipath (see Figure 2), and second, we have the ability to craft different types of filters which can better extract the desired signal from the noise. Figure 5 shows two conditions similar to those of Figure 3. We show a so-called linear frequency modulated (LFM) waveform arriving over the same two paths used with the CW pings. The lower plots show the output of the special filter used with these LFM waveforms. The sharp peak identifies the arrival time of the signal, and its height relative to noise is a measure of output SNR, which is nearly the same in both conditions.

It is important to note that the transmitter electronics must be more capable than with the current pinger design, and the receiver must (generally) be built around a micro-computer, such as a digital signal processor (DSP). However, even when operated at approximately the same center frequency, and transmitted with the same power, the signal should be detectable at several kilometers, rather than (at best) the one kilometer of the present system. Equally important, the use of signals such as the LFM permit the transmission of considerably more energy than a simple CW transmitter can provide (via longer, but lower power transmission).

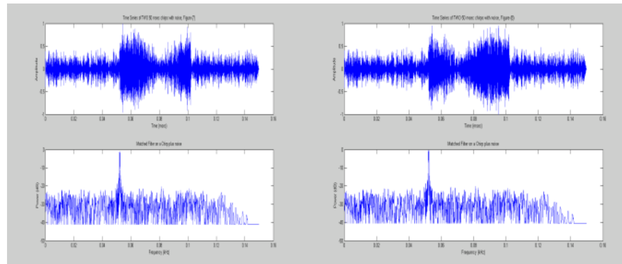

Figure 5. Two examples of an LFM signal in noise arriving over two paths with subtly different arrival times. In both cases, the signal is equally detectable.

Using broadband signals substantially overcomes multipath issues and provides a major increase in SNR for a given range resolution. However, waveforms such as an LFM can create substantial multi-access (mutual interference) problems. One solution is for the UUV to sequentially request ranges from the several transponders. However, the motion of the UUV then requires an internal model to remove distance covered during each of the transmissions. This can result in very unsatisfactory performance.

In the following section we describe three signaling schemes used in the Telesonar modem, one being frequency hopping, frequency shift keying (FH/FSK), another being multi-channel M-ary frequency shift keying (generally simply called MFSK), and the third being M-ary phase shift keying (MPSK). Pertinent to the previous discussion, the frequency hopping method provides a very robust, high resolution, high gain, multi-access solution for LBL localization. This is a standard capability in Teledyne Benthos’ navigation aid for our deep-tow survey sensors.

3 Modulation

We first describe the modulation techniques used in the Telesonar modem. Three quite distinct modulations schemes each 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.

3.1 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 for approximately 80 bps of (true) data rate. Our scheme uses a pseudo-random frequency placement for the tones, and we employ a number of similar tonals as a precursor for signal acquisition and alignment.

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 6 shows a simple example in the time-frequency plane where M = 2 (binary).

3.2 Multi-Channel M-ary FSK

The term 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

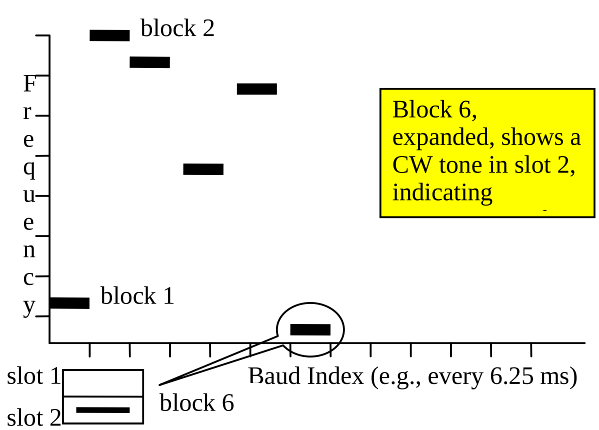

Figure 6. Example of Frequency-Hopped Binary FSK.

'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 7 provides an example of this method.

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.

3.3 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

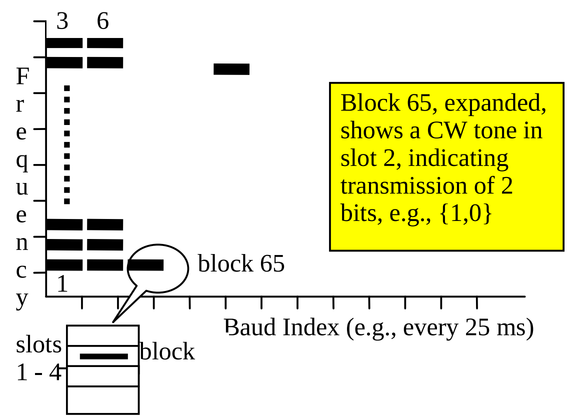

Figure 7. Example M=4 MFSK scheme transmitting 2 symbols with each tone.

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.

3.4 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 (LPM) waveform. This is processed with a "matched filter" using as a filter an exact replica of the transmitted LPM. 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.

3.5 Channel impulse response estimation

The output of the broadband matched filter may be interpreted as a band-limited estimate of the channel impulse response (IR). For example, Figure 8 shows six plots, each of which shows the output of a matched filter applied to a series of closely-spaced received braodband signals. The upper left-hand and lower right-hand plots show reference signals obtained from a distance of 1 meter. The others show signals received from a source positioned approximately 100 m distant, in approximately 30 meters of water. These plots show both SNR (discussed below) and estimates of the channel impulse response. We estimate the duration of the IR by first estimating the start of the IR (it may not be at the strongest peak), then computing the point at which, for example, 95% of the energy is observed to represent the duration. With a drifting surface ship supporting the receiving hydrophone, it is apparent that the IR changes dramatically, but our algorithm does a credible job of correctly estimating the duration.

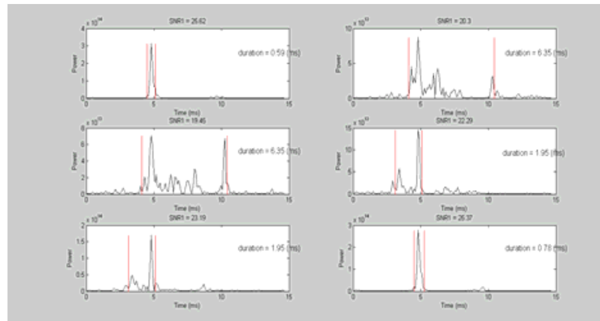

Figure 8. Estmates of the channel impulse response based upon a band-limited matched filter applied to a chirp signal

3.6 SNR estimation

One may estimate the output *SNRo* for a matched filter <u>squared</u> output *Z* from

$$SNRo = ((Pz - Mz)/\sigma z),$$

where *Pz* is the peak signal plus noise output, *Mz* is the mean of the noise (only), and σ*z* is the standard deviation of the noise (only) output. The input *SNRi* may then be estimated via the

simple relationship

$$\text{SNRo} = \text{SNRi}*(\text{TWs})$$

where *T* is the duration of the signal (chirp) and *Ws* is the bandwidth spanned by the signal. This estimate is valid for additive Gaussian white noise in the absence of multipath, but it is a reasonably good indicator of "true" SNR under many real-world conditions.

4 Application of Acomms Signaling in Navigation

We discuss three different navigation aids based around our acomms technology: an underwater equivalent to GPS, an enhanced LBL, and a broadband USBL system. Among the many attributes of these broadband methods, the fact that they are tightly integrated with a communications scheme reduces the false alarm rate to near zero.

4.1 Multi-Access Signaling

There are three parts to the transmitted signal: a broadcast acquisition portion, a transmitter identification portion, and the message. There is a brief time gap between each section. All portions of the signals are frequency hopping components, as described above. In the case discussed, the acquisition and middle sections each require 20 hops. The message requires 216 hops. Each hop requires the transmission of a single tone for 6.25 ms. The time gaps are 12.5 ms in duration. The complete signal requires 1.6 seconds. Figure 9 shows a superposition ofapproximately 30 tones from two different transmitters indicating the lack of collisions. In this case there is only a single collision.

We observe now that the number of hops used in a waveform is dictated by the physics of the channel. It can be shown that, in a near-worst case Rayleigh-fading environment (i.e., severe multipath), only about 13 chips are required to provide nearly the same level of detectability that would occur in an additive white Gaussian noise (AWGN) channel (i.e., no multipath). Obviously, as the number of chips increases, so too does reliability. We choose to use 20 chips as a compromise.

It is essential to observe that the multi-tone FH acquisition signal is almost immune to frequency-dependent fading. We emphasize this point to distinguish this approach from simple systems, such as a pinger, that transmits a single tone at one frequency; these systems can (and do) completely fade from view at unfortunate combinations of multipath arrivals. Furthermore, the presence of multiple pingers, all at the same frequency, induces mutual interference and general confusion.

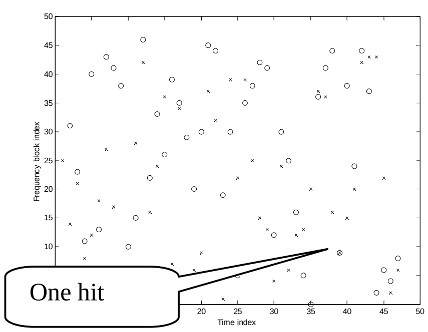

Figure 9. An example of two colliding waveforms presented in the time-frequency plane

The multi-access value of the FH approach is further demonstrated in Figure 10, which shows performance of 3 (fully) overlapped signals of equal power in the presence of white noise in a mild multipath environment. There were 20 realizations at each SNR point. The nubers on the graph (0 or 1) indicate the number of failed packets out of the 20.

Even with one desired signal being 6 dB weaker than the other two, performance is still comparable, indicating that SNR is the dominant constraint on performance.

4.2 Underwater GPS

We have demonstrated that our CDMA signal built as an FH/FSK waveform supports asynchronous, multi-access communications. In this section we demonstrate how effective it can be in implementing an underwater equivalent to GPS. In 2008 we constructed three small buoys and equipped each with a GPS receiver, and an acoustic modem. As shown in Figure 10, these buoys were placed approximately 400 meters apart, in a shallow waterway approximately 10 meters deep (each buoy is shown centered within a different colored circle). A small boat equipped with its own GPS towed a modem on a 15 meter cable while traveling at about 4 kts. At a predetermined interval of 30 seconds, the three buoys transmitted their own geolocations simultaneously using our FH/FSK scheme. The towed modem, acting as a surrogate UUV, received these three signals, demodulated and decoded them, and solved a non-linear equation to establish the position of the modem. The figure shows the boat's own estimate of its track (orange track), superimposed with the modem's estimate (green track). No correction has been made for the spatial ofset between the boat's GPS and the position of the towed modem. Our conclusion is that the system performed well within the tolerances imposed by the satellite GPS accuracy, and indeed, this is the limiting constraint on system performance in shallow water.

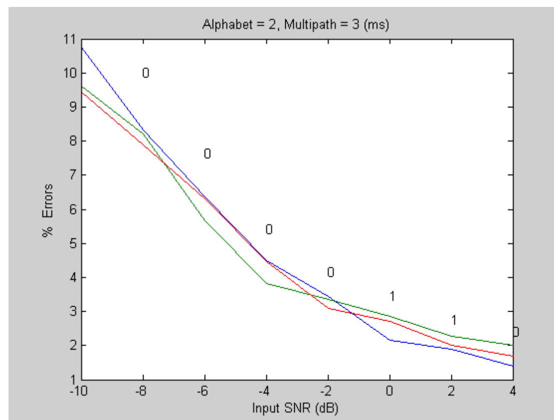

Figure 10. Performance in a mild multipath channel, with all signals received at the same power level. In general, the percent of symbol errors is low enough that one would expect successful error correction out to an SNR of –8 dB. This represents an increase in required SNR of approximately 6 dB relative to an ideal channel.

We note, as indicated before, that there were no extraneous measurements ("false alarms") during this experiment.

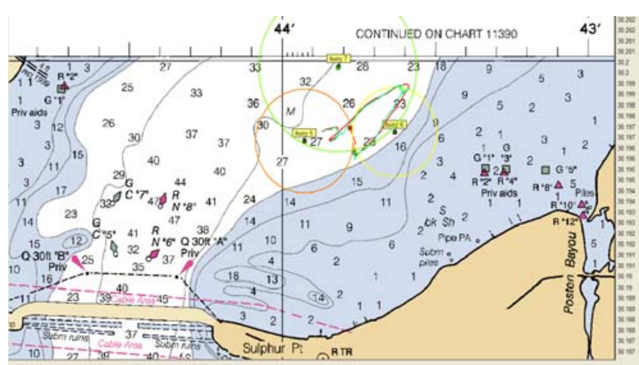

Figure 10. An underwater GPS demonstration

4.3 Broadband Multiaccess LBL

In previous sections we described the rudiments of LBL positioning and discussed the limitations of tonal signaling.

As mentioned, tonal signals are often used not only because they are inexpensive, but also because it is possible to receive multiple tonals (through non-overlapping filters) as a means of locating multiple transponders.

At Teledyne Benthos we are now replacing tonal transponders with FH and FH/FSK signaling. This also permits the use of simultaneously-received signals through the multi-access (CDMA) quality of these waveforms, but equally as import, we obtain considerable "processing gain" through the acquisition process. We therefore effectively enhance the received SNR over a simple tonal while avoiding frequency-dependent fading. We also significantly improve range estimation accuracy for a given transmit source level.

4.4 Broadband USBL

The Directional Acoustic Transponder (DAT) 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" 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.[1] [2] 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 ± 2 degree and the vertical accuracy is approximately ± 2 degrees.

We note, but do not show, that FH signaling will also work very well with the DAT, although angle of arrival accuracy is somewhat reduced.

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 DAT with a range command, the DAT responds with a message containing the received angles. The requesting modem estimates range based on the turn-around time. The DAT 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 DAT 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 DAT 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 DAT 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/Dat receives a range request from a remote modem, it automatically responds with the estimated angles.

The DAT 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 11 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 12, 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. Figures 13-15 show various present-day DAT applications.

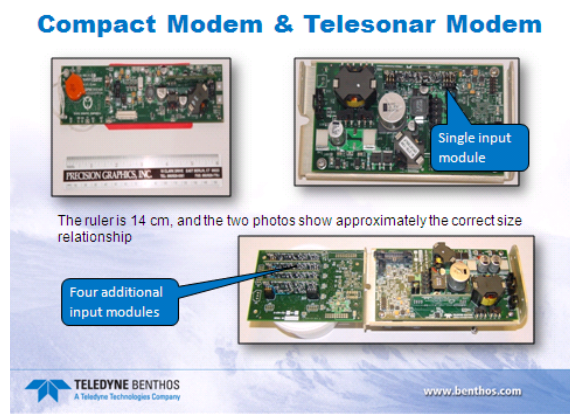

Figure 11. Photographs of various DAT and other modem components

Figure 12. All modem components, including wet-end.

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[1] T. Austin, "The Application of Spread Spectrum Signaling Techniques To Underwater Acoustic Navigation," Oceans 1994

[2] US Patent #7,362,653 B2

5 Conclusions

The technologies and concepts embedded in underwater acoustic communications offer major improvements in the performance of navigation aids long based on simple tonal signaling. In particular, we have shown that spread spectrum signaling (FH and FH/FSK) permits asynchronous, multi-access use of transponders, LBL system, and underwater GPS in ways that drive false alarm rates nearly to zero.

We have also shown that the use of broadband signaling can provide major improvement in USBL performance, especially when tightly integrated with acoustic communications, and we have noted that FH and FH/FSK signaling can also be used effectively with a USBL system.

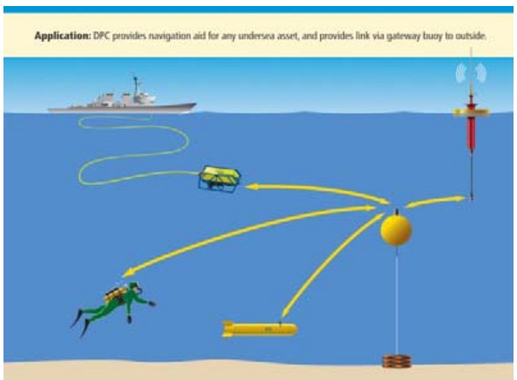

Figure 13. Navigation aid for many varieties of underwater platform

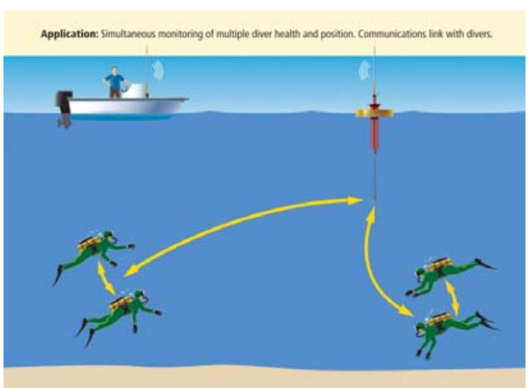

Figure 14. Diver Tracking

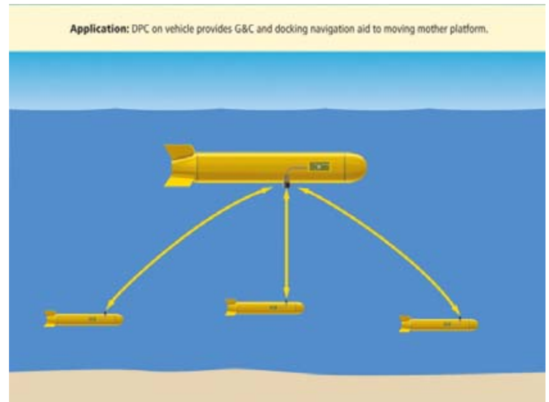

Figure 15. Guiding and docking multiple UUVs