Underwater Acoustic Communication and Modem-Based Navigation Aids

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Abstract. New forms of navigation aids for underwater vehicles are enabled through the use of acoustic communications. Both the content and form of the message may be used to estimate range, bearing, range rate, geo-location, and time. Accurate range estimates are available via a conventional 2-way method, but the transmitted signal also supports high precision bearing estimation and highly accurate range rate compensation at the receiver. A new multi-access waveform supports asynchronous and simultaneous reception and processing of multiple messages leading to translation of conventional satellite GPS to the underwater environment. High accuracy tracking of underwater vehicles is enabled through a further modification of this multi-access signal. Recent advances in DSP-based, low-power modem development provide a rich infrastructure for accomplishing these navigation functions simultaneously with a variety of communications functions. Each of these developments are supported by recent at-sea experiments and demonstrations

1 Introduction

In this paper we describe several practical navigation aids, each based upon our core acoustic communications technology. The technology is the result of numerous programs funded over the past ten years by the US Navy, as well as by substantial IR&D programs within Teledyne Benthos. The fundamental requirement for all of these inter-related efforts is the use of physically small, battery-powered, DSP-based hardware. The acoustic communications provides connectivity under most environmental conditions at data rates ranging from 80 bits per second (bps) to in excess of 10 Kbps. The navigation functions each involve novel developments in broadband acoustic signal processing. These include a broadband enhancement to an ultra-short baseline (USBL) bearing estimator, precision range estimation, precision estimation of and compensation for very high relative speed platforms (i.e., high range rate), translation of GPS to the underwater environment, and precision tracking of underwater vehicles. Each of these systems have been tested at sea with excellent results.

Section 2 describes some of the capabilities of the Telesonar modem, and highlights those signaling characteristics used to implement the navigation aids. Section 3 describes three recently-developed navigation aids, along with results of recent at-sea experiments. Finally, Section 4 describes certain ongoing developments affecting both communications and navigation aids for undersea platforms.

2 Acoustic Signaling

The navigations aids described later in this paper use either of two non-coherent signaling schemes that are standard signaling formats in the Telesonar modem. The first is a frequency hopped, frequency shift keyed (FH/FSK) signal which is used either for extremely adverse channels or for multi-access situations. It is an inherently low data rate scheme, but one which tolerates a variety of linear and nonlinear processing designed to reduce the affects of interference and low SNR. In the Telesonar formulation, a pseudo-random hopping pattern, based upon finite field arithmetic, is used to position individual tonals (sinusoids) at discrete frequencies within a constrained bandwidth. Only one tonal is transmitted at one baud period. For the standard case of 6.25 ms tonals, combined with error correction coding, we transmit at approximately 80 bps. A typical operating bandwidth is 5120 Hz. Figure 1 shows a graphical formulation of a typical FH/FSK (binary) modulation.

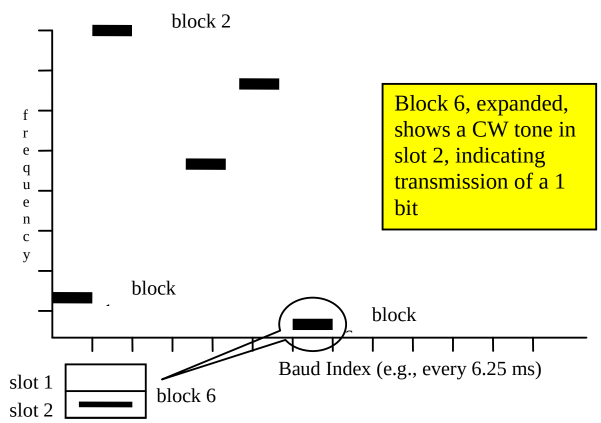

Fig. 1. Example of frequency-hopped binary FSK.

The remarkable feature of the hopping patterns used here is that several signals can co-exist simultaneously within the same time- and frequency-space. The Telesonar modem is able to acquire and process four such signals at the same time.

The second type of signal is the standard Telesonar signaling scheme which is known as MFSK. Although the details of the modulation are not pertinent to the navigation aid discussion, for completeness this is described by Figure 2. Here, we generate 32 tones for each baud period. The structure supports signaling from 140 bps to 2400 bps. Most users find that 600 bps to 800 bps suffices for most environments. For the navigation-related signaling, such as a range request, we always use the 140 bps rate with an 8-byte packet.

There are auxiliary waveforms associated with the MFSK signal which are separate from the modulated portion. In particular, the modulated portion is preceded by several tones and a hyperbolic chirp. The latter is fundamental to three aspects of our combined communications and navigation schemes:

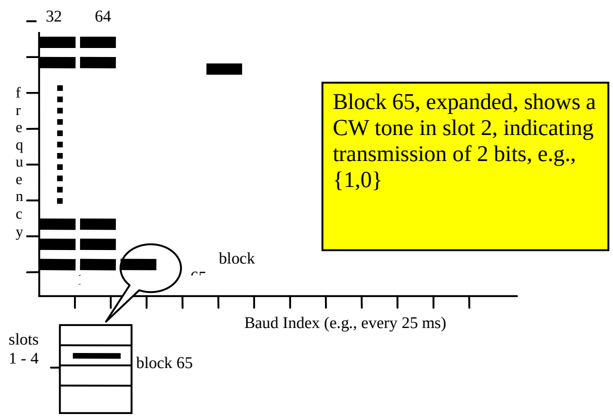

Fig. 2. Example of M=4 MFSK scheme transmitting two symbols with each tone.

1 Temporal and spectral synchronization and range rate alignment.

   a. Replica correlation-based processing, with additional processing described best in US Patent #7,218,574 "High Range Rate Signaling."

2 Range measurement between two modems.

   a. Range accuracy fundamentally limited by the inverse of the chirp bandwidth, which typically is 5120 Hz, or 0.2 ms in time.

   b. Accuracy also depends on precisely known "turn-around time" within the electronics. This typically is known to within 0.05 ms error.

3 Bearing measurement of an arriving modem signal.

   a. This is more fully described in section 3, following.

For completeness, the Telesonar modem also provides several varieties of phase shift keyed (PSK) signaling, with data rates between approximately 2500 bps to 10 kbps. Although all modems can transmit such waveforms, the receive algorithms (typically of the decision feedback (DFE) variety) are only available in a deckbox or buoy configuration.

3 Navigation Aids

Four different modem-based navigation aids are discussed in this section. The first provides a portable tracking range for verifying the internal navigation performance of underwater vehicles. The second provides a translation of conventional satellite-based GPS to the underwater environment. The third provides a means for a platform to query a remote device to obtain position, and the fourth combines elements of the third to enable both group awareness (autonomy) and precision tracking of remote modems.

3.1 Portable Undersea Tracking System (PUTS)

The portable tracking range, under development for NUWC Keyport[1] since 2006, employs modems to provide real-time position information to submarines without the need for inter-node cabling, external processing or support systems that are required by existing ranges. This system, portrayed in Figure 3 is comprised of standard SM 75 units[2]. For a submarine to determine its position, it transmits a “range” request with a conventional MFSK signal identifying up to 6 remotes in the message. The remotes respond with one of six FH signals available, depending upon the order in which the remotes were addressed. All 6 responses are processed simultaneously on the submarine to obtain ranges to each remote. Since the processor on the submarine is programmed with the geo-position of all remotes, it can then compute its position. This system includes a new transducer design and modem concept that utilizes just 2 wires between modem electronics and the transducer in place of the previous 8 wires. This, combined with a new deck-box containing a modem and other electronics, forms the core components of the submarine-based portion.

[1] PUTS, SBIR Phase 3 contract N00253-06-R-0004, TPOC Mr. Doug Ray, NAVSEA Division Keyport, an OSD program.
[2] Smart Modem model 75

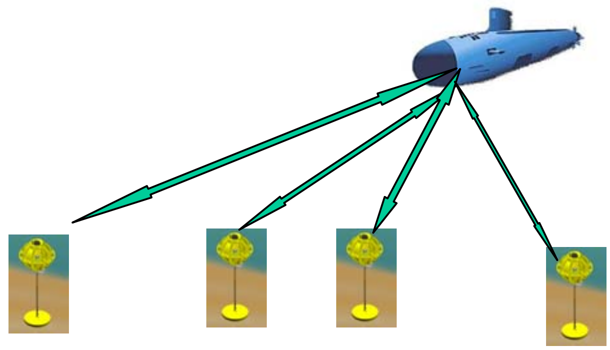

Fig. 3. Portable tracking range concept.

A major consideration for PUTS success is the implementation of Benthos patented technology for accommodating high range rate (relative speed) encounters. This technology was developed with internal Teledyne funds, and has since become standard in all Telesonar and Seaweb modems.

3.2 Directional Acoustic Transponder (DAT) and Smart Marker

Although separate programs, the DAT and SM recently have been demonstrated together, so we discuss them together here. The Smart Marker (SM)[3] project started in 2002 and developed a customized modem providing low-power extended operations for marking underwater objects. This is a "next-generation" marker that, in contrast to traditional analog responders, allows individually addressable units (in the same broad frequency band) using digital IDs for identification of individual units within a field, and the broadband signaling provides greater ranges and immunity to noise. Low-power and extended operations are enabled by reducing the modem's power output and by the incorporation of advanced sleep modes.

The DAT is designed to be a single point replacement for a multi-node long baseline (LBL) navigation system. It operates in either of two ways. In the first, it queries a remote modem, or, in the present case a Smart Marker, returns a conventional modem ranging response. The DAT includes three (or more) small hydrophones used in a (modified) USBL method to estimate the arrival angle of the response. The two-way travel time is used to estimate the range. In the second method, a remote modem queries the DAT, which immediately estimates the bearing and returns that to the originating modem. Range is obtained from the two-way travel time. For the demonstration, the first method was used.

Figure 4 shows a solid edge drawing of the "wet end" of a DAT. The various components are indicated. Figure 5 shows a photograph of a Smart Marker. The total

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[3] ONR SBIR topic N02-207 "Smart Marker", phase II contract N00014-04-C-0111, Program Manager Dr. Thomas Swean (ONR), TPOC Dr. Brian Bourgeois (NRL)

length of the latter is approximately 30 cm. Both of these devices are designed to operate in the 22 – 27 kHz band, although lower frequencies are readily available as well.

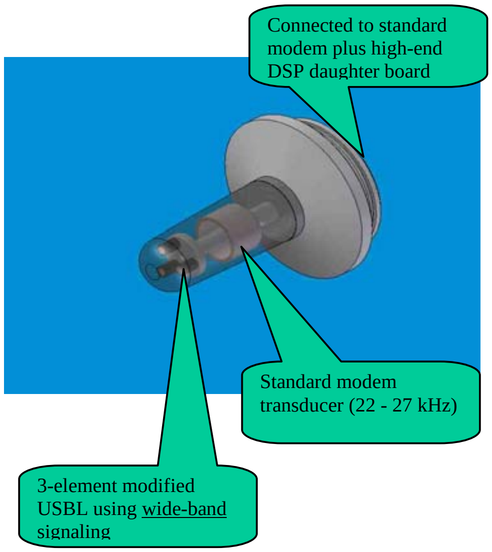

Fig. 4. DAT wet end, a portion of a system designed to provide communications, range, and bearing to and from a remote modem or Smart Marker.

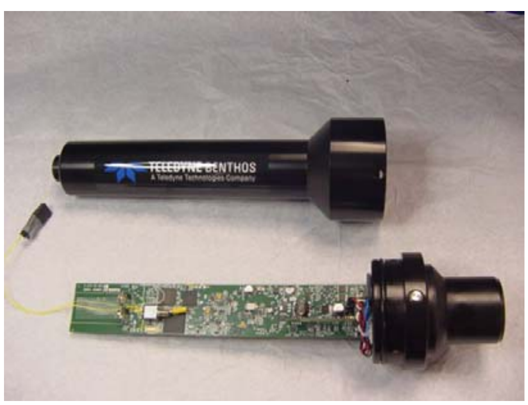

Fig. 5. Smart Marker, essentially a reduced size, lower power modem used as an object marker in underwater environments.

A combined exercise was conducted with the DAT and the Smart Marker seaward of the surf zone in water between 3 and 8 meter depth. The DAT was placed on an underwater robotic crawler as shown in Figure 6. The Smart Marker was positioned on a 1 meter high tripod further out to sea. The crawler, towing a surface float and radio link and carrying a video camera, was driven through the surf. The DAT on the crawler was commanded to query the Smart Marker. Range and bearing were obtained. The crawler moved approximately 50% of the indicated range, along the direction indicated, then the DAT was queried again. This was repeated until the crawler moved DIRECTLY to the Smart Marker. The first acquisition occurred at 100 m range. As shown in this figure, the Smart Marker had toppled over and was partially buried in the sand. We note that an earlier exercise, which consisted of communicating with the Smart Marker from a nearby pier (shown in the figure), achieved perfect links at 328 m, at all of the available data rates, up to and including 2400 bps (true information rate). We thus assume that the crawler-based DAT would have found the marker from a considerably greater range had it not fallen over. We wish to emphasize that the crawler was commanded to follow precisely the DAT-indicated bearings. No "fudge factors" whatsoever were employed.

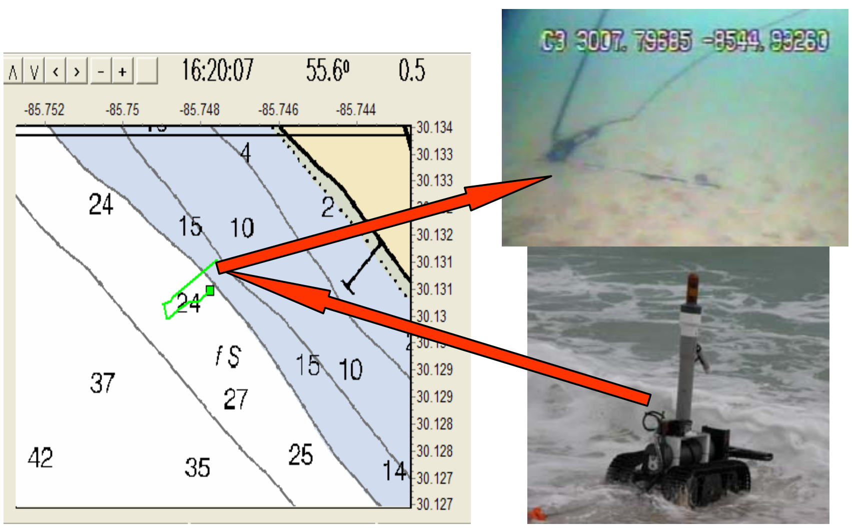

Fig. 6. DAT and Smart Marker demonstration at AUVFEST 2007 in the surf and shallow water environment off of Panama City, Florida.

We note that the with the DAT carried on a cooperating fleet of underwater vehicles or divers, all participants obtain bearing to any other participant with each transmission, and any can query another for both range and bearing. This support UUV autonomy with both communications and location, and not only provides a group of divers with the same information, but as well provides the dive master with a real-time overview of the dive team's locations and activities.

3.3 Underwater GPS (UW/GPS)

The UW/GPS is effectively a translation of satellite GPS to the underwater realm. We place 3 or 4 surface buoys in a polygon bracketing an operating area. Each buoy is equipped with a GPS receiver (to obtain position, time, and 1 PPS signals), and an acoustic modem. At a specified instant (say, every 30 seconds), all of the modems simultaneously transmit their own positions using a Frequency hopping (multi-access) waveform. A passing vehicle with a modem on board, and without benefit of a synchronized clock, can extract each of the signals from the presence of the others and, knowing its own depth, can estimate it geo-position.

In this demonstration, we placed the three buoys in a northern portion of St. Andrews Bay and used a boat to carry an over-the-side modem as a surrogate UUV. The boat was kept at minimum forward speed, and conducted the exercise shown in part in Figure 7. Because the boat-based modem was equipped with its own GPS, we were able to develop a reasonable version of "ground truth," as indicated by the red line. The blue line shows the estimate the UUV would make, given the same received geo-positions.

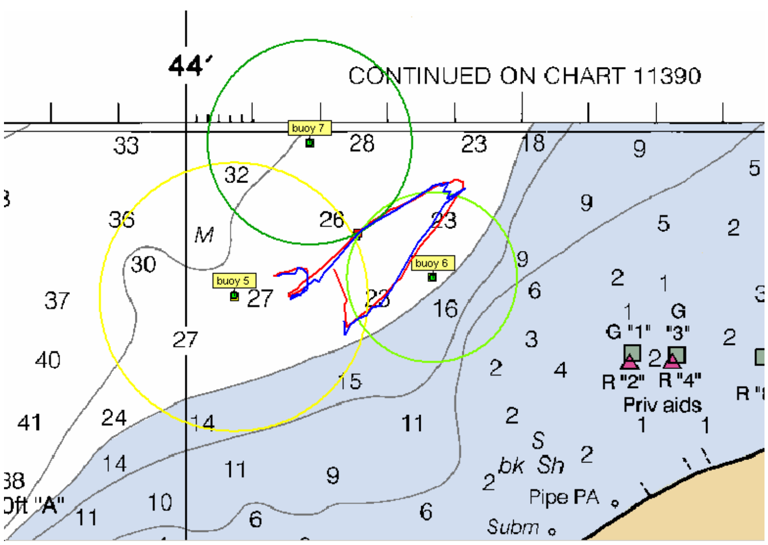

Fig. 7. Underwater GPS performance at AUVFEST 2007, with three buoys and a surrogate AUV. Buoys are approximately 400 meters apart, water and depth in feet.

We note that our version of "truth" does not account for the error in buoy positions (derived from ordinary satellite GPS) nor for the towed modem, which was at least 4 meters (horizontal) and 3 meters (vertical) removed from the boat-based GPS receiver.

4 Summary

We have described several practical navigation aids, each based upon our core acoustic communications technology. Each has been demonstrated to be an effective, high performance alternative to existing conventional technology. The PUTS system, while still under development, has been repeatedly tested and shown to perform as designed – position accuracy is very good, and large scale deployments have been funded.. The DAT, when carried on a UUV, is simple and easy to use. In this version it merely requires calibration to point to the nose of the vehicle. In the alternative version, it is placed on the sea floor as an addressable beacon, and calibration is provided simply by informing it acoustically of the direction of true North. At the frequencies used (22 – 27 kHz), it is small and unobtrusive, although we can provide a system at any frequency below this. The performance of the DAT is fundamentally limited by the physical size of the small hydrophones. At the current frequency they are rather large with respect to the carrier frequency wavelength. This development is continuing through new US Navy programs.

The Smart Marker performed flawlessly, both as a marker and as a modem. We have exciting opportunities to convert this marker into a new generation of "Compact Modem" for tagging and diver communications purposes, both of which are now under development.

The UW/GPS system performed very well. This is shown to be a reliable, easily-deployed, and unobtrusive system (the UUV only carries a modem). The buoys performed perfectly. As they have, in the past, carried RF modems as well, they are very suitable as gateway buoys for protected waters.