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Underwater Navigation using Pseudolite

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ABSTRACT

Using pseudolite or pseudo satellite, a proven technology for ground and space applications for the augmentation of GPS, is proposed for underwater navigation. Global positioning systems (GPS) like positioning for underwater system, needs minimum of four pseudolite-ranging signals for pseudo-range and accumulated delta range measurements. Using four such measurements and using the models of underwater attenuation and delays, the navigation solution can be found. However, for application where the one-way ranging does not give good accuracy, alternative algorithms based upon the bi-directional and self-difference ranging is proposed using self-calibrated pseudolite array algorithm. The hardware configuration is proposed for pseudolite transceiver for making the self-calibrated array. The pseudolite array, fixed or moored under the sea, can give position fixing similar to GPS for underwater applications.

Keywords: pseudolite, navigation, underwater communication, underwater navigation, pseudo satellite

1. INTRODUCTION

Most of the earth's surface is covered by water. The world's oceans that hold vast resources, are a major regulator of our climate. However, the oceans are relatively unexplored and less understood, in large part because of the difficulty of communicating and navigating underwater. The underwater navigation using low-cost INS is not accurate and safe for military purpose as it frequently needs the GPS update. To get the GPS update underwater vehicle need to come above the water level, which may not be desirable for military applications? The majority of navigation underwater is being performed for short ranges using acoustic positioning system. The long-range underwater navigation is still an open area for research. Researchers are focusing towards modellling the propagation delays. The predictable propagation delays can be compensated in navigation solution similar to GPS, where the ionospheric and tropospheric propagation delays are compensated in navigation solution algorithm using Kalman filter.

2. LITERATURE REVIEW

The underwater communication has been investigated since long using acoustic, radiowave, blue-green light, and optical signals. Almost all underwater communications use acoustics due to its low attenuation for long distances. Radiowaves are not able to travel long due to their strong attenuation in salt water[1]. Long-wave radio, however, can be used for short distances; for example, 1–8 kbits/s at 122 kHz carrier for ranges[1] up to 6–10 m. Underwater optical communication is also a promising mode of underwater communication for very low-cost, short-range connections[2] of order 1–2 m at 57.6 kbits/s. It is reported that for longer ranges and more typical water clarity, acoustic communication is the only practical method. A rough performance limit for current acoustic communications is the limit of 40 km·kbps for the range-rate product, though this mostly applies to vertical channels in deep water, and it dramatically overestimates the performance in difficult shallow water, horizontal channels[3]. The frequency dependent noises changes with time due to surface waves or vehicle motion which causes fading to under water acoustic wave. To cater for time varying frequency dependent noise and hence mitigating the effect of fading, specialized decision feedback equalizers and phase locked-loops are required[4]. While multipath interference is mostly a source of difficulty, recent work using arrays for both transmit and receive multiple-input, multiple-output (MIMO) takes advantage of the independent channels created by different multipaths to increase throughput[4]. Over longer paths, frequency-dependent attenuation can suppress certain propagation modes, leading to shadow zones, or spatial regions where almost no acoustic signal exists. Also, strong attenuation (on the order of 20 dB/m or even higher, persisting for tens of seconds) can occur in near-surface regions with bubble clouds, which are entrained into the water by breaking waves[5].

Although the underwater acoustic channel is time-varying, propagation delays can be modelled like ionospheric, tropospheric, multipath, etc as in the case of GPS above the water, and are stable enough to use for navigation purpose. Underwater navigation is still an emerging area and lot of research work is going around the globe, especially for long-range applications. Currently, few techniques exist for

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Table 1. Instruments used for underwater navigation[6]

Instrument	variable	Internal	Update rate	Precision	Range	Drift
Acoustic altimeter	z-Altitude	Yes	Varies 0.1-10 Hz	0.01-1.0 m	Varies with frequency	-
Pressure sensor	z-depth	Yes	Medium:1 Hz	0.01%	Full ocean depth	-
Inclinometer	Roll, Pitch	Yes	Fast:1-10 Hz	0.1^{o}-1^{o}	+/- 45^{o}	-
Magnetic compass	Heading	Yes	Medium 1-2 Hz	1^{o}-10^{o}	360^{o}	-
Gyro (Mechanical)	Heading	Yes	Fast:1-10 Hz	0.1^{o}-0.01^{o}	360^{o}	10^{o}/h
Gyro (North Seeking)	Heading,Pitch, Roll	Yes	Fast:1-100 Hz	0.1^{o}-0.01^{o}	360^{o}	-
Gyro RLG/FOG	Heading	Yes	Fast:1-1600 Hz	0.1^{o}-0.01^{o}	360^{o}	0.5^{o}/h
12 KHz LBL	XYZ position	No	Varies 0.1 to 1 Hz	0.1 –10 m	5-10 Km	-
300 KHz LBL	XYZ position	No	Varies 1.0 to 10 Hz	+/- .007 m	100 m	-
Bottom lock Doppler	Body velocity	Yes	Fast:1-5 Hz	0.3% or less	Varies 18-200 m	0.2-0.4%
GPS	XYZ	No	Fast 1-10 Hz	0.1-10 m	In water 0 m	-

reliable 3-D position sensing for underwater vehicles. Table I summarises the sensors most commonly used to measure a vehicle's six degree-of-freedom (DOFs) position. While depth, altitude, heading, and attitude are instrumented with high bandwidth internal sensors, position sensing is usually achieved by acoustically interrogating fixed, seafloor-mounted transponder beacons[6]. Inertial navigation systems are not suitable for long-range and long-duration missions. GPS is well known for its application above water but its signal gets attenuate rapidly in water, and thus, these cannot be directly received by deep underwater vehicle platform. Recent work suggests that the next generation of acoustic communication networks will provide position estimation along with data telemetry[7]. The standard method for full ocean depth acoustic navigation is 12 kHz long baseline (LBL) acoustic navigation[6]. The 12 kHz LBL typically operates up to 10 km range with a range-dependent precision of 0.1 m to 10 m and update rate periods[6] as long as 20 s. Currently, the best method for obtaining sub-centimeter position sensing is to employ a high-frequency (typically 300 kHz or greater) LBL system. Experiments show that these systems are capable of sub centimeter precision and update rates[8] up to 10 Hz. Unfortunately, due to the rapid attenuation of higher frequency sound in water, high-frequency LBL systems typically have a very limited maximum range[6]. All absolute acoustic navigation methods require careful placement of transponders, fixed or moored, on the seafloor[9]. The fundamental limitation of low speed of sound wave (1500 m/s) results into low update rate of position fixing. This necessitates that the acoustic positioning system may be used to augment the inertial system similar to GPS/INS integration scheme for above water application.

3. LINK COMPUTATION FOR ACOUSTIC TRANSCIEVER

To have the ranging and navigation message transmission among the acoustic transceiver, link calculation need to be done. Link budgeting is an established method of analysing performance in wireless and satellite communications. Link budgets are a design tool to predict signal-to-noise ratio (SNR) at a receiver given system parameters such as transmit power and antenna gain, and channel parameters such as propagation loss and interference. This predicted SNR is compared to a minimum required SNR to obtain a link margin.

The process of establishing a link margin for reliable communications is readily applied to the acoustic communications system. The difference is that the terms are now acoustic quantities. Once the acoustic SNR is transformed to an electrical quantity, it can be compared to establish a link margin[10].

3.1 Parameters Specific to Acoustic Link Budget

3.1.1 Directivity Index

The directivity index (DI) may be defined as the ratio of the intensity of a source in some specified direction (usually along the acoustic axis of the source) to the intensity at the same point in space of an omni-directional point source with the same acoustic power. Through the principle of reciprocity, the same principle applies to the receiving transducer. The transmitter DI_{xmt} and DI_{rcv} receiver directivity, and are analogous to the RF terms for antenna gain.

3.1.2 Pressure Spectrum Level

Pressure spectrum level (*PSL*) is a function of input power and transmission bandwidth. PSL for a pure broadband signal would be represented as $PSL = SL - 10 \log (W)$, where W is bandwidth of the signal.

3.1.3 Received SNR

The acoustic link budget uses basic sonar theory to estimate the available signal level at the receiver. The basis of the model is the sonar equation, $SNR=PSL-TL-AN+ DI_{xmt} + DI_{rcv}$

where *SNR* is signal-to-noise ratio at receiver, *PSL* is pressure spectrum level, *TL* is transmission loss in the medium, DI_{xmt} and DI_{rcv} are transmitter and receiver directivity, respectively. All quantities are expressed in dB re 1 micro pascal.

3.1.4 Transmission Loss

The transmitted signal pattern has been modelled in various ways, ranging from cylindrical one to a spherical one. Spherical spreading of the signal is assumed to exist up to a range equal to water depth of the channel. Beyond this range, cylindrical spreading is assumed to exist by virtue of the bounded propagation medium. Spherical spreading loss is proportional to $1/r^2$ and is expressed as

$TL_{sphere} = 20.\ \log_{10}(r)$

Attenuation in seawater is caused by three mechanisms: shear viscosity, volume viscosity, and ionic relaxation[10]. As shown by Robert [11], absorption in seawater is frequency-dependent and is modelled by the expression

$$\alpha = \frac{0.11 f^2}{1+f^2} + \frac{44 f^2}{4100+f^2} + 3.0\times10^{-4} f^2 + 3.3\times10^{-3}$$

where α is the attenuation coefficient in dB/km and *f* is frequency in kHz.

The loss due to attenuation in seawater is expressed as $TL_{atten} = \alpha \times r \times 10^{-3}$ where *r* is range in meters.

3.1.5 Ambient Noise

Frequency-dependent ambient noise (*AN*) can be estimated for various wind speeds and shipping densities using the spectral relationships compiled by Waite[12]. Because communication frequencies are dominated by wind-driven noise, AN varies greatly with wind speed[10]. A rough figure of 60 dB ambient noise may be used for 15-20 KHz frequency range[10] up to wind speed of 20 knots. Typical link calculation comparison is given in Table 2.

4. POSITION COMPUTATION

The use of sonar for position fixing is well known techniques for underwater platform. However, the localisation like GPS is still not possible for an underwater platform. This is mainly due to the fact that one-way underwater propagation model is not sufficient to provide the accuracy as in the case of GPS. A bi-directional and self-differencing ranging mechanism to cancel out the uncompensated propagation delays using pseudolite transceiver is proposed. The un-modelled common mode errors get cancelled if these ensure that the outgoing and incoming waves pass through the same propagation media. The simplest navigation solution using self–differencing transceivers directly determines the range between the antennas on a pair of devices themselves. Figure 1 shows such a pair of devices.

The measurements taken by each receiver of the signals from the two pseudolites are given as

$$\begin{Bmatrix} \Phi_i^i \\ \Phi_i^j \\ \Phi_j^i \\ \Phi_j^j \end{Bmatrix} = \begin{Bmatrix} 0 \\ R_{ij} \\ 0 \\ R_{ji} \end{Bmatrix} + \begin{Bmatrix} b_i^i \\ b_i^j \\ b_j^i \\ b_j^j \end{Bmatrix} + \begin{Bmatrix} \tau^i \\ \tau^j \\ \tau^i \\ \tau^j \end{Bmatrix} + \begin{Bmatrix} \tau_i \\ \tau_i \\ \tau_j \\ \tau_j \end{Bmatrix}$$

where, b_i^j : Line bias from PL *j* to Rec *i*; R_{ij} : Range between modem antennas; Φ_i^j : Rec *i*'s measurement of PL *j*; τ^j: Clock bias of PL *j* ; τ_i: Clock bias of Rec *i*.

Eliminating any receiver clock bias or common mode effects by taking internal single (self) differences between the signals received by a given receiver, as shown

$$\Delta\Phi_i = \Phi_i^j - \Phi_i^i = (b_i^j - b_i^i) + (\tau^j - \tau^i) + R_{ij} \quad (1)$$

$$\Delta\Phi_j = \Phi_j^j - \Phi_j^i = (b_j^j - b_j^i) + (\tau^j - \tau^i) - R_{ij} \quad (2)$$

Combining the measurements from both receivers and rearranging Eqns 1 and 2, one can determine both range between the antenna pair and the relative clock bias of the pseudolites.

Table 2. Typical link calculation comparison for pseudolite above and below water applications

Design parameters for pseudolite on ground (RF mode)	Design parameters for pseudolite underwater (Acoustic mode)
$P_r = P_t + G_t + G_r$ - Path loss -160 dB= P_t + 6 + 3 – 152 dB i.e P_t=17 dBm Noise temperature=513K For distance *d* = 600 km P_t=17 dBm ~ 20 dBm *f* = 1.5 GHz	*SNR* = *PSL* - *TL* - *AN* + DI_{xmt} + DI_{rcv} -6 dB = PSL - 15 - 60 + 0 + 0 PSL = 15 + 60 - 6 = 69 dB P_t = 37.8 dB for distance *d* = 100 km where TL = is 0.15 dB/km, and AN is Ambient noise is 60 dB for 15-20 kHz at 20 Knots wind velocity *f* = 15 kHz to 20 kHz

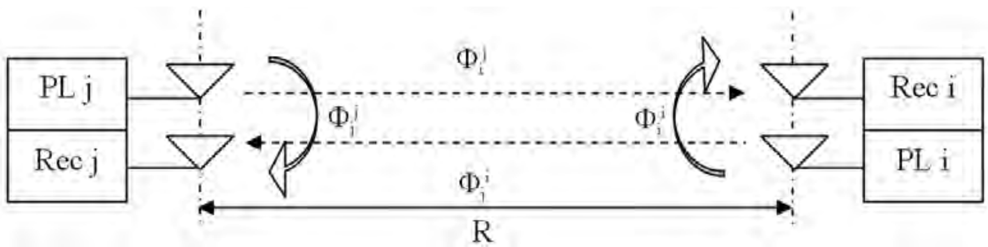

Figure 1. Self-differencing and bi-directional ranging mechanism.

$$\begin{Bmatrix} \tau^{j} & \tau^{i} \\ R_{ij} & \end{Bmatrix} = \frac{1}{2}\begin{pmatrix} 1 & 1 \\ 1 & 1 \end{pmatrix}\left\{\begin{Bmatrix} \Delta\Phi_{i} \\ \Delta\Phi_{j} \end{Bmatrix}\begin{Bmatrix} b_{i}^{j} - & b_{j}^{i} \\ b_{j}^{j} - & b_{j}^{i} \end{Bmatrix}\right\} \tag{3}$$

Equation 3 can be utilised to compute the position of one of the pseudolites which is mounted on the underwater vehicle whose position needs to be computed by knowing the position of the other pseudolites.

5. PSEUDOLITE TRANSCIEVER ARCHITECTURE FOR UNDERWATER APPLICATION

GPS transceiver, which combines the function of a GPS receiver and PL, has been proposed[13]. Such GPS transceivers could communicate and synchronise each other, and then estimate relative positions using the ranging information among them. The architecture for underwater application shall be designed such that the bi-directional and self-differencing is possible with separate transmitter and receiver components, as shown in Fig. 2. The RF front-end of the pseudolite transceiver[13] shall be replaced with acoustic modem. The output of the acoustic modem transmitter is split, with one line going to a passive broadcast antenna and the other going to one front end on the dual front-end acoustic modem receiver for self-differencing, as required by Eqns (1) and (2). This allows the acoustic modem receiver to monitor the output signal, effectively measuring the relative clock bias between the acoustic modem transmitter and its own receiver. The other acoustic modem receiver end is connected to an antenna that listens for signals from the other acoustic modem.

6. CONCEPT OF OPEARATION

Figure 3 illustrates the concept of operation. The pseudolite arrays can be fixed or moored on an underwater platform which is supposed to be stationary or drifting. The reference ship is required once for self-calibration of the pseudolite array. The calibration of the pseudolite array will give the position and clock biases of the entire pseudolite arrays participating in the calibration process. Once calibration is over, the pseudolite arrays can operate independent of the reference ship. One of the pseudolites in the arrays can be mounted on the moving underwater platform whose position needs to be computed

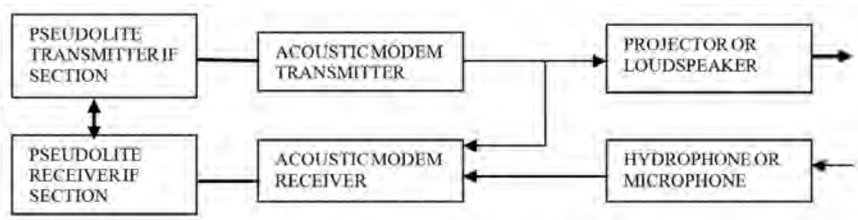

Figure 2. Modified pseudolite transceiver architecture.

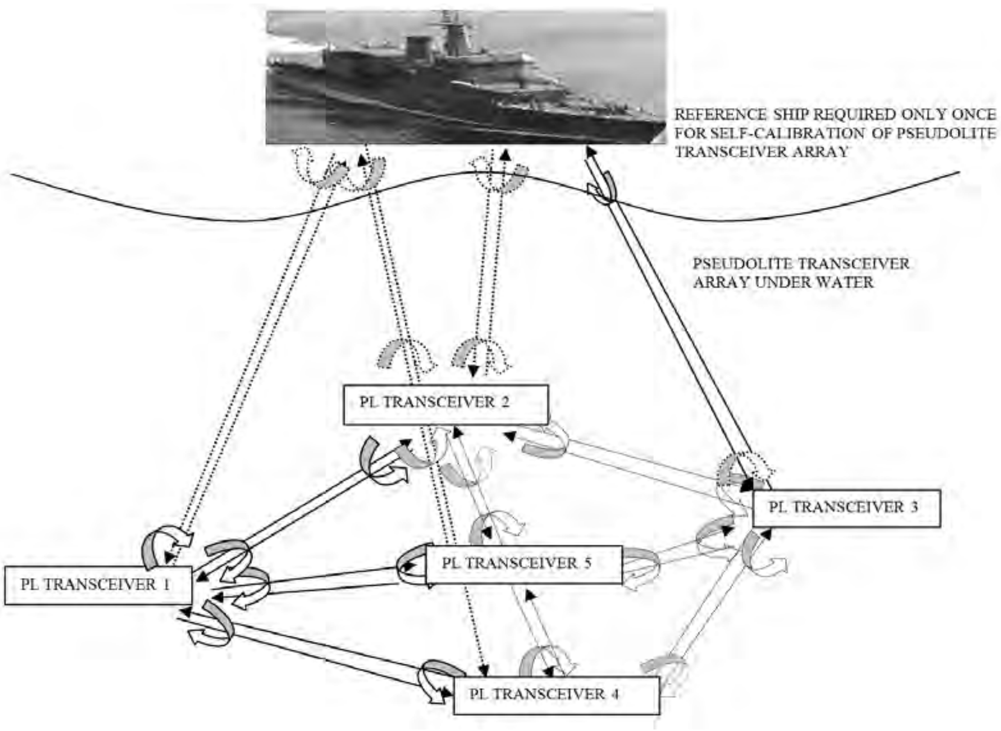

Figure 3. Deployment of pseudolite transceiver for underwater navigation concept.

using Eqn (3). Here, the absolute or relative both positioning is possible. The number of participating paseudolite arrays also can be arbitrarily chosen based upon the mission requirement.

The pseudolite transceiver concept is extended for the availability of GPS-type positioning systems for underwater localisation applications. Conventional GPS pseudolite arrays require that the devices be pre-calibrated through a survey of their locations, typically to sub-centimeter accuracy. This can sometimes be a difficult task for underwater environments. Using the pseudolites broadcast mounted on the reference ship, however, it is possible to have the array self-survey its own relative locations, creating a self-calibrating pseudolite array (SCPA) in an underwater environment.

7. CONCLUSIONS

Underwater navigation using pseudolite transceiver has been proposed. The link budget has been presented to justify that the existing acoustic modem can be used along with pseudolite transceiver to communicate between the two transceivers which are separated 100 km. The two-way ranging mechanism minimises most of the common mode unknown propagation delay errors and ambient noise. The conventional pseudolite transceiver hardware need to be modified to receive and transmit the acoustic signals.

The self-calibrated pseudolite array algorithm has been proposed to find the position of pseudolite transceiver which is mounted on the underwater vehicle whose position needs to be found. The pseudolite self-calibrations ensure the accurate position finding of all the participating pseudolite arrays whose initial positions are unknown.

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