Two Reference points Underwater Positioning System for Swarming AUVs Team Operation

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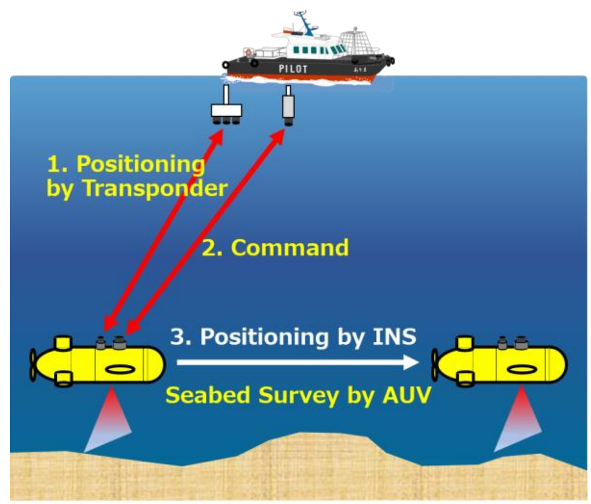
***Abstract*— This paper describes an Underwater Positioning System for plural AUVs with swarming operation. Although a conventional Underwater Positioning System needs more than three known reference points by Long Base Line (LBL) method, the proposed system only needs two GNSS supported reference points. Then the reference points of the system can be configured with only one Ship and one Buoy towed by it. However, the system additionally makes use of depth information and distance information between AUVs. Targeting system configuration is with two reference points (BS1 and BS2) and three AUVs (UE1, UE2, UE3) arranged in a triangle. The system is composed of OFDM-based Down Link (DL) and Up Link (UL) communication function to deliver GNSS information, commands etc. and Distance measurement function between all nodes by sending 10ms special sequence such as Chirp between BS and UEs as DL and Zadoff-Chu (ZC) sequence between UEs as Side Link (SL). Intensive computer-based signal processing simulation has been performed for two scenarios such as 70 m shallow case and 3000 m deep case. The simulation result has shown that any UE can identify it's and other UEs' positions even SL's Carrier to Noise Ratio CNR= 0dB with DL's CNR=6dB.**

Keywords—Underwater Positioning, Acoustic Communication, OFDM, AUV, Swarming

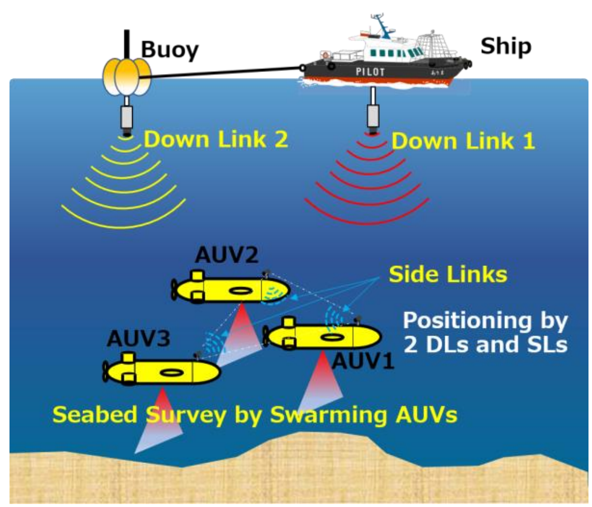
I. Introduction

In the seafloor lies expansive regions that have been unexplored. In order to create fine seafloor topographic maps, deep sea area such as more than 3000 meter must be scanned by Autonomous Underwater Vehicles (AUVs) close to the seabed. Because Global Navigation Satellite System (GNSS) cannot be used in underwater, special underwater positioning system [1] is mandatory. Fig. 1(a) shows conventional AUV operation using an Inertial Navigation System (INS) [2]. When the AUV has dived to the desired depth starting point, the position of the AUV may be measured by the transponder response. Then AUV can start scanning the seabed while the position is kept track by the high accuracy INS system with heavy tracking computation.

This paper proposes a new underwater positioning system which does not use INS in order to realize a compact and lower cost AUVs, and additionally realizes AUV swarming operation. Fig. 1(b) is the proposed Two Reference points Underwater Positioning System with three AUVs swarming operation. The system is composed of two Down Link (DL) acoustic signals and AUV to AUV Side Link (SL) acoustic signals. The two DL sounds are sent alternately every one or a few seconds from a Ship and the towed Buoy, whose positions are GNSS tracked.



(a) Conventional AUV operation by Inertial Navigation System (INS)



(b) Proposed Positioning System for Swarming AUV operation using two Down Link signals without INS.

Fig. 1: Conventional INS based AUV Seabed Survey and Proposed Two Reference points Underwater Positioning System for Swarming AUVs.

II. Operation of Two Reference Points Underwater Positioning System

Fig. 2 shows a topological relation of all nodes in the system. BS and UE stand for Base Station and User Equipment, respectively. The all distances between any two nodes are shown in the figure, which are measured by DL and SL signals. The sound sequences starting from DL1 signal from BS1 (Ship) are shown in the Fig. 3. The sound sequences from BS2 (Buoy) are the same but not shown in figure. Note that the distance symbols in Fig. 2 such as r11, r12, …, a, b, c are shown as a corresponding delay time in Fig. 3. The DL packet is composed of Chirp signal

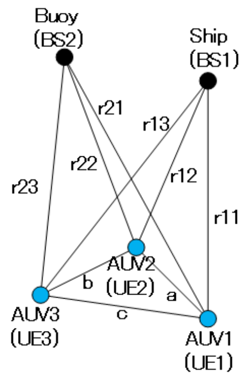


Fig. 2: Distances between All Nodes, which are measured by the System.

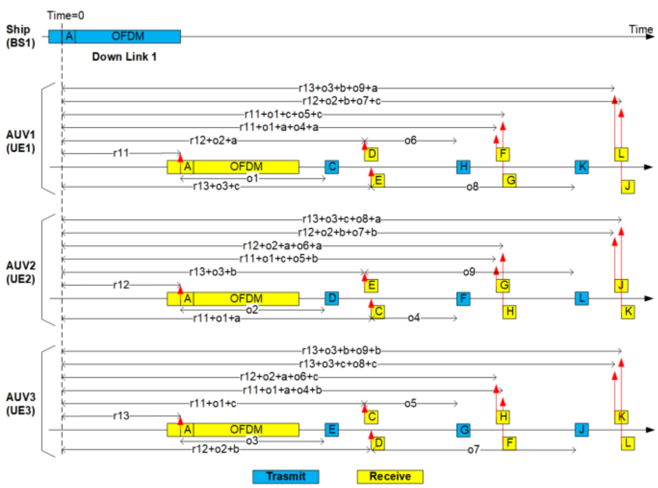


Fig. 3: Down Link and Side Link Signal Timing Diagram.

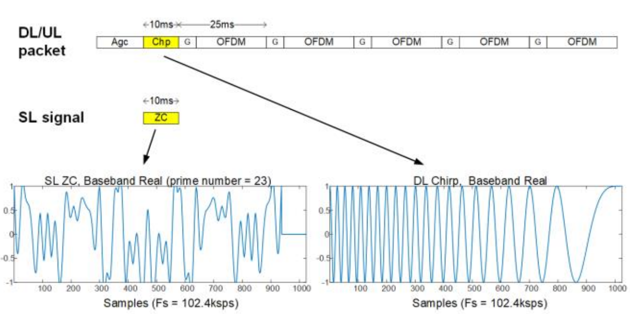


Fig. 4: Signaling Packets and Timing Detection Reference Signals

Table I: Underwater Positioning System Parameters

Parameters	Value
Signal Band	16kHz±4kHz
Sampling Frequency	102.4k Hz
DL reference signal	10.0ms Chirp
SL reference signal	10.0ms Zadoff-Chu (N_{ZC}=73) 9 types (prime numbers = 23/29/37/41/43/47/53/61/67)
OFDM symbol length T	20.0 ms (2048 points)
FFT Size	2048
GI length Tg	5.0 ms (512 points)
Effective Symbol length Tu=T+Tg	25.0 ms
Sub Carrier Spacing	50.0 Hz
Number of Sub Carrier	161
Number of Pilot in OFDM symbol	Zadoff –Chu, N_{ZC}= 81 and 13
Down Link OFDM packet size	5 OFDM symbols
Forward Error Correction	Convolution Code (k=7, R=1/2)
Sub Carrier Modulation	QPSK
Packet Data Size	596 bit

‘A’ and OFDM communication signals [3-7]. All UEs will receive the DL packet and measure the delay times between BS1 and each UEs such as r11, r12, r13. The OFDM packet carries BS1’s time and position information, which is obtained from GNSS. Because of the clocks of BS and UE are synchronized, each UE can detect the exact delay times.

After detecting signal ‘A’, each AUV send signal C or D or E to other AUVs with delay o1, o2, o3. By detecting the C, D, and E signals from nearby AUVs, the timings indicated by the red arrow in Fig. 3 can be measured. By repeating the above SL two more times using signal F, G, H, J, K, and L, the all red-arrow timings can be measured. Afterall each AUV has 7 measured timings. By using those 7 timing, 6 distances (delay times) such as r11, r12, r13, a, b, c can be solved in each AUV independently. Similarly, another Down Link 2 from BS2 will perform the same operation. Then r21, r22, r23, a, b, c distances also can be obtained. However, the position of the AUV cannot be determined only by measuring these distances. By taking each UE’s depth into account, two sets of UEs triangle positions can be solved. UEs triangular position sequence can be seen as Clock Wise (CW) or Counter Clock Wise (CCW) according to the two sets solutions. If the rotation sequence is known, one position solution can be obtained. To set UEs’ CC or CCW placement, each UE includes a function of direction detection of other UEs. The detail will be shown in the next section.

Fig. 4 indicates DL and SL signal packets. DL contains the Chirp signal ‘A’ and OFDM communication signal because Chirp signal can be easily detected under Doppler shift conditions. SL is composed of just one 10ms detecting signal and Zadoff-Chu (ZC) sequence is used since those SL signals has to be detected in overlapping conditions. Signal C, D, E, F, G, H, J, K, and L are ZC sequences corresponding to a different prime number. Table I shows detail parameters of Underwater Positioning System. The acoustic signal bandwidth is 8kHz and the center frequency is 16kHz. The 2048-point OFDM symbol

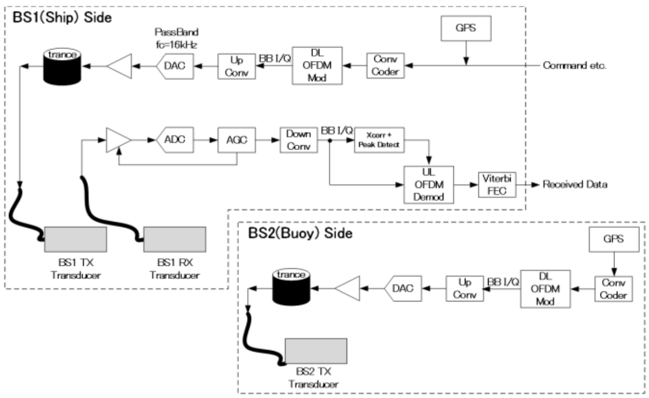


Fig. 5: Ship(BS1) and Buoy(BS2) Signal Processing Block Diagram.

length is 20.0 ms with Guard Interval of 5.0 ms . Number of total sub carrier is 161 and sub carrier spacing is 50 Hz. The 5 OFDM symbols packet carries 596 bit data with QPSK modulation and R=1/2 Convolutional Code forward error correction [8].

III. System Design

BS side signal processing diagram is shown in Fig. 5. BS1 side has both transmitting (TX) and receiving (RX) functions. The receiver is to monitor UEs condition at long time interval since the transmission of signal from UE to BS1 consumes relatively high power comparing with SL powers. BS2 has only transmitting function to generate DL2 signal with embedding GNSS information. Fig 6 shows UE side signal processing diagram. Two elements transducer is newly developed. Ha branch is used for RX and TX for OFDM communication. Both Ha and Hb branches are used for detecting SL signals. Not only to detect absolute timings for distance measurement but also to detect incoming signals phase difference is detected to get directional information of incoming SL signals. As explained in the previous section, this direction detection function will be used to setup the triangular location of UEs such as CCW or CW. Ha and Hb receiver has matched filters (cross correlator) with 11 templates such as ‘A’ (BS1 chirp), B (BS2 chirp), C to L (9 ZC sequences) .

Fig.7 shows the two elements transducer photo for UEs. The transducer design is based on OST2120 transducer of Oki Seatec and Ha / Hb two branches are integrated in one body. Fig. 8 shows the System board for UEs using Xilinx Zynq ARM-embedded FPGA device.

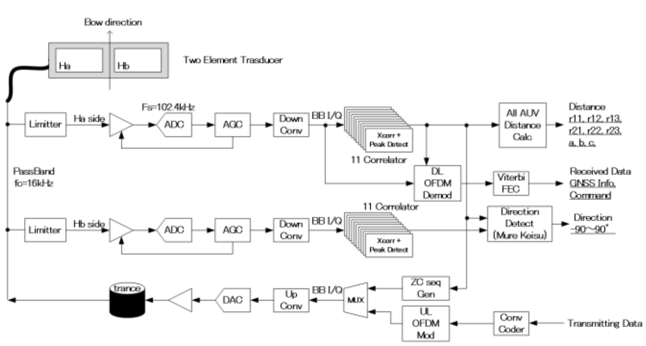


Fig. 6: AUV(UE) side Signal Processing Block Diagram.

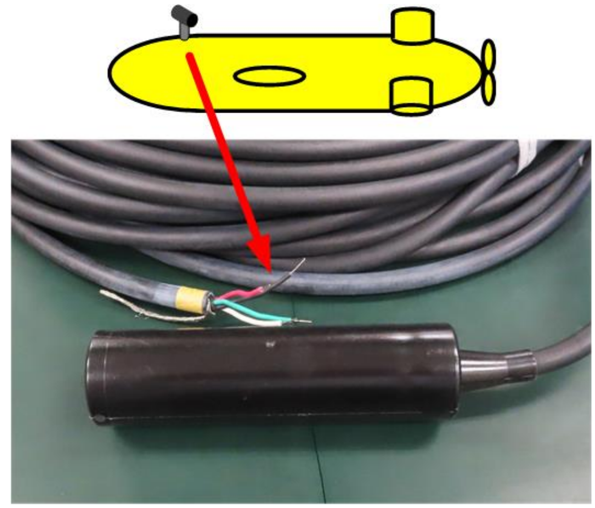


Fig. 7: AUV(UE) side Two Elements Transducer Photo for Direction Detection.

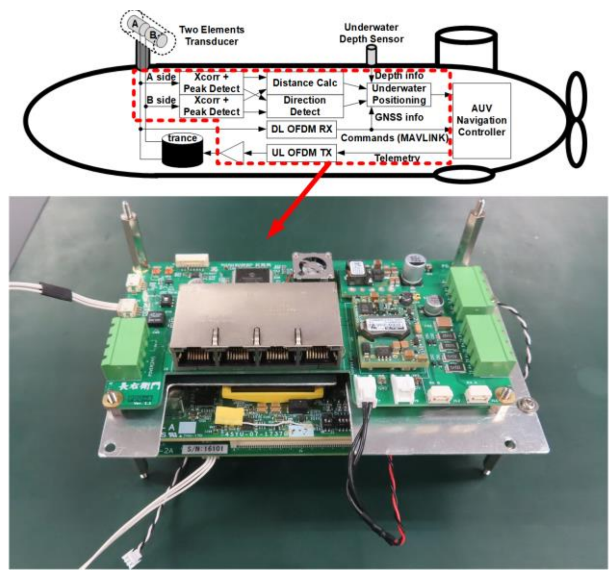


Fig. 8: AUV(UE) side System Board Photo.

IV. Computer Simulation

In this section, two scenarios for the proposed positioning system and its’ simulated results are shown. Table II summaries parameters of the scenarios and Fig. 9 shows the corresponding setups. Case 1 in Fig. 9(a) corresponds to Shallow and Small

Table II: Two scenarios for Computer Simulations

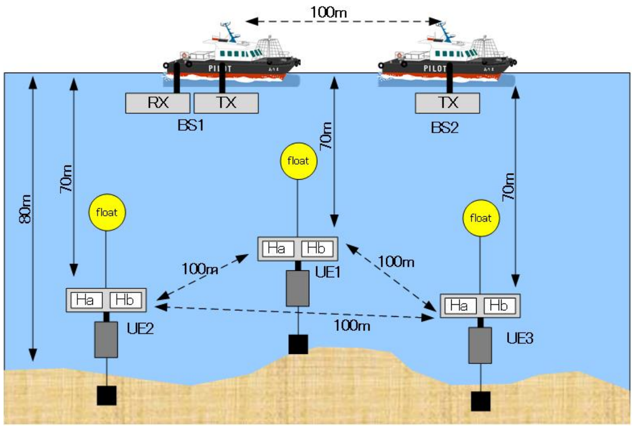
Parameters	Case1 Shallow Small	Case 2 Deep Large
BS1 to BS2	100 m	600m
UE Depth	70 m	3000 m
UE to UE	~ 100 m	~ 600 m
DL CNR (dB)	6 dB	6 dB
SL CNR (dB)	7 to -3 dB	7 to -2 dB

area. In addition, we plan to perform Ocean field experiment with case 1 setup in this fall to winter. All UEs are floated from the seabed with a few meter distance. UE intervals are roughly 100m and depth is 70m. Case 2 setup as shown in Fig 9(b) corresponds to deep and large area. Since UE to UE distance is 600 m, swarming three AUVs can scan seafloor of 1000 m width using a Multibeam echosounder (assuming 200m to seabed and more than 90 degree fan-beam). In case 2, BS1 to BS2 distance of 600m is assumed.

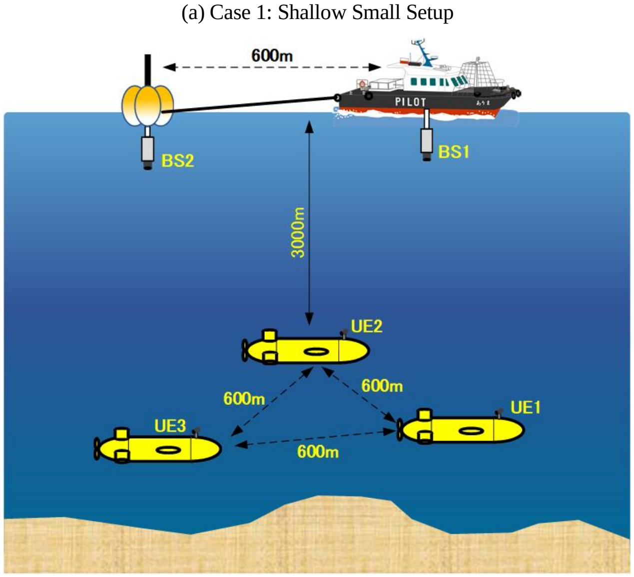
Simulated signal waveforms of BS1, UE1, UE2 and UE3 are shown in Fig.10(a) for Case 1 and Fig. 10(b) for Case 2. Time Axis of (a) is 0 to 1 sec and that of (b) is 0 to 4 sec. Because of 3000m depth in Case 2, roughly 2 sec of propagation delay is required. Control delays of o1 to o9 are optimally set for each case. Blue waves mean TX signals and red waves correspond to RX waves. BS2 Down Link and corresponding operations are not shown in the figures. However, in the simulation BS1 to BS2 interval is 2.0 sec.

Then simulated Down Link OFDM Packet Bit Error Rate performance is shown in Fig. 11. Sub Carrier modulation is QPSK and Convolutional encoder with Constraint length K=7, Code Rate R=1/2 is used as forward error correction. At the receiver side Soft decision Viterbi decoder is used. In the range of Carrier power to Noise power Ratio (CNR) more than 6 dB, error free is achieved. Then, in the following SL simulations, DL CNR of 6dB is used.

Fig. 12 shows the simulated positioning errors for 2 cases. In the system, 3 AUVs' positions are estimated in each AUV. The

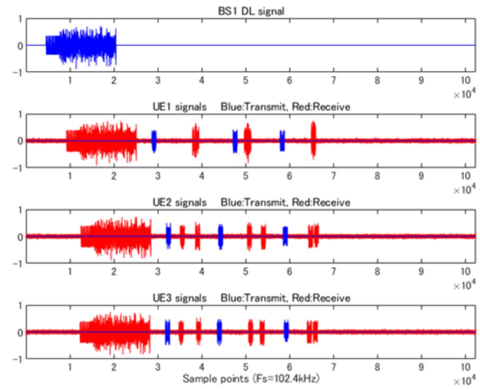


(a) Case 1: Shallow Small Setup

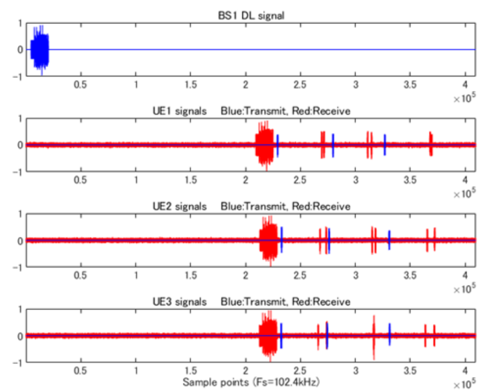


(b) Case 2: Deep Large Setup

Fig. 9: Two Swarming AUVs Team Setups.



(a) Simulated Waveform for Case 1



(b) Simulated Waveform for Case 2

Fig. 10: DL and SL simulated waveform for Two Cases.

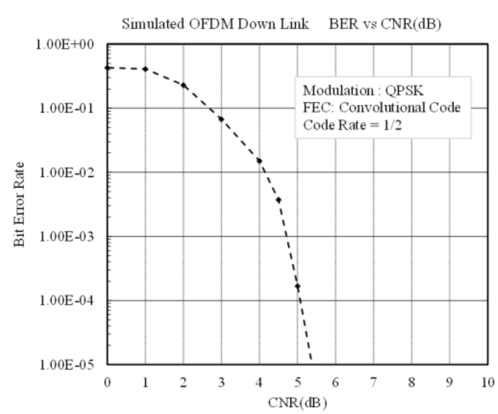
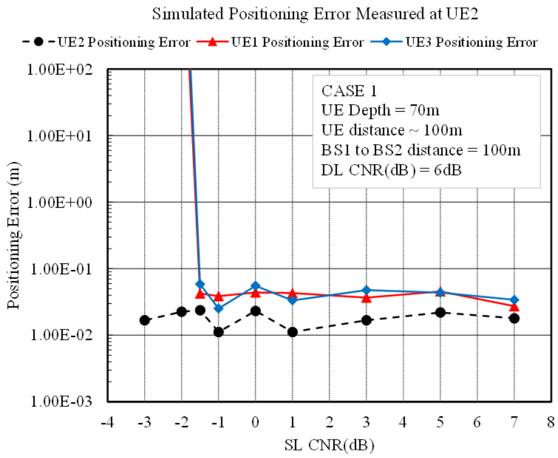
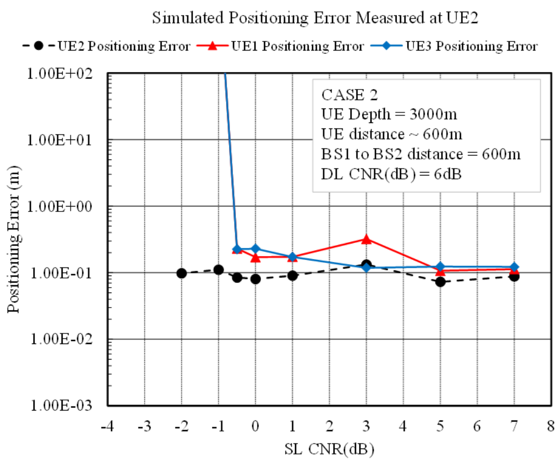


Fig. 11: Simulated DL Bit Error Rates



(a) Simulated Positioning Error for Case 1



(b) Simulated Positioning Error for Case 2

Fig. 12: UE1/UE2/UE3 Positioning Error Calculated using only Measured Results at UE2.

figures indicate 3 UEs' positioning errors which are calculated in UE2. UE2 position can be calculated by measured r12 and r22 length with UE2's depth. Since UE2's positioning error has no dependency on SL CNR (dB), both Fig. 12(a) and (b) show UE2's flat characteristics. UE1's and UE3's positioning errors are determined by all measured length such as r11, r12, r13, r21, r22, r23, a, b and c. Then These two positioning errors are depend on SL CNR (dB). For case 1: Shallow Small Setup, at the condition of SL CNR more than −1.0 dB, positioning error is less than 0.1m. For case 2: Deep Large Setup, at the condition of SL CNR more than 0.0 dB, positioning error is less than 0.4m. Since the simulations assume that acoustic sound propagation speed, which is the function of Ambient temperature, Salinity and Water pressure, is perfectly estimated, the simulation results has shown system positioning error lower bound.

V. Conclusion

This paper describes an new Two Reference points Underwater Positioning System for plural swarming AUVs. Although a conventional Underwater Positioning System needs more than three known reference points by Long Base Line (LBL) method [1] or high accuracy INS [2] with heavy tracking computation, the proposed system only needs two GNSS supported reference points and does not need high accuracy INS. Then the reference points of the system can be configured with only one Ship and one Buoy towed by it.

Our targeting system configuration is with two reference points (BS1 and BS2) and three AUVs (UE1, UE2, UE3) arranged in a triangular shape. The system is composed of OFDM-based Down Link (DL) and Up Link (UL) communication function to deliver GNSS information, commands, monitoring data etc. and Distance measurement function between all nodes by sending 10ms special timing detection sequence such as Chirp between BSs and UEs as DL; and Zadoff-Chu (ZC) sequence between UEs as Side Link (SL). Intensive computer-based signal processing simulation has been performed for two scenarios such as 70 m Shallow Small case 1 and 3000 m Deep Large case 2. The simulation result has shown that any UE can calculate it's and other UEs' positions successfully with SL's Carrier to Noise Ratio CNR= 0dB with DL's CNR=6dB.

Acknowledgments

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