BLUEMED

Activity 3.6
Design and implementation of the augmented diving service for Underwater Museums

Deliverable 3.6.1
Report on the customization of the long baseline (LBL) acoustic positioning for underwater tablet localization

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1. Foreword

According to BLUEMED's project proposal, Activity 3.6 is devoted to the design and the implementation of the augmented diving service for an Underwater Museum.

Specifically, Deliverable 3.6.1 describes the details of the customization required to allow an acoustic modem to be able to localize a diver, and in particular its tablet, via a long baseline (LBL) acoustic localization system. In the first part of this report, the positioning system developed in the VISAS project [1] will be described. After that, the customization to be undertaken for allowing the positioning system developed in the VISA project to comply with the BLUEMED prescriptions and goals will be detailed.

2. Technology Review

2.1 Underwater Localization systems

The underwater positioning tools currently available on the market are based on very expensive acoustic communication systems, which estimate the position of the receiver by computing the distance from at least three fixed transmitters.

Three different primary geometries are used for acoustic localization systems: Ultra Short Baseline (USBL), Long Baseline (LBL) and Short Baseline (SBL) [5]. The distance between the active sensing elements (transmitters/receivers) is called the acoustic baseline. The typical baselines for the various systems are reported in the following table.

Positioning System	Baseline Length
USBL	<5 cm
SBL	1-10 m
LBL	50m – 1Km

USBL systems consist of a transducer array, with the transducers placed ~ 5 cm apart, thus the name ultra-short baseline. There are generally at least three transducers in this array, which is called the transceiver. A transducer placed on the target to be localized acoustically pings the transceiver and receives a response. The travel time is used to calculate its distance to the transceiver. However, just the distance information is not enough to estimate the position in an inertial frame. The angle or direction information is also required. To accomplish this task, a technique called phase-differencing is used. In this technique, the angles of arrival of the acoustic pulse from the AUV transducer to each transducer of the transceiver are used to discern the direction. Hence, the distance and direction are together used to calculate the receiver position. USBL systems are easy to deploy and are the most widely used localizat systems. However, because the baseline is small, they are less accurate than SBL or LBL systems.

On the contrary, Long-baseline (LBL) positioning refers to the determination of position via interrogation of two or more fixed transducers separated by large distances (long baselines). LBL systems can be broadly classified into two types, based on where the fixed/static transducers are deployed.

- Classical LBL systems, where the transponders are moored to the seabed and fixed to the bottom.
- Mobile LBL systems, where buoys equipped with GPS (GIBs) are deployed on the water surface with the transponders submerged in the water at a determined depth.

Classical LBL systems require a precise knowledge of the bathymetry of the area of operations. The transponders are deployed on the ocean floor and their topology needs to be accurately known. The distances between the transponders, their depths and positions are used to set up a local reference frame upon which the receiver position is estimated. The accuracy of the transponders

position introduces is an important source of error and inaccurate values they may deeply impact on the overall accuracy of the system. Classical LBL systems require a lot of time and efforts to successfully be deployed and are not easily portable. To overcome these difficulties mobile systems are sometimes preferable.

In *Mobile LBL* systems, the beacons/buoys (GIBs) float on the water surface with the transponders submerged in the water. They are generally anchored to the ocean floor to restrict their movements due to currents. The transponders can be submerged at predetermined depths. GIBs remove the need for the LBL beacons to be installed at the seafloor, a feature that can reduce deployment costs. Since the GIBs are also equipped with GPS, it becomes easier to establish a local position frame. The process of localization is similar to that in SBL systems. The moving transducer pings each of the transponders in the LBL system in a round-robin fashion. The travel times of the response signals are used to estimate its position.

SBL systems are characterized by an acoustic baseline length of 1-10m. In these systems a set of acoustic transponders are mounted on the underside of a ship, boat or of any sufficiently large floating platform or buoy. They use TOAs of the acoustic signals from each of these transducers to the transducer mounted on the moving unit to compute its position via trilateration. The accuracy of the computation is largely dependent on the length of the baseline. Generally, the farther apart the transducers, the better the accuracy. The position is calculated relatively to the GPS position of the host vessel/buoy and requires a precise calibration of the transducer array. Depth sensors on-board of the moving unit are used in conjunction with the acoustic travel times to obtain 3D position information. SBL systems require operating in the close vicinity of the ship and having a lower range than LBL systems. However, they are easier to be deployed and operate and are favored for research operations centered around a host vessel/buoy.

2.2 VISAS Positioning System

VISAS (Virtual and Augmented Exploitation of Submerged Archaeological Sites) [1] is a collaborative research project funded in 2014-2016 by the Italian Ministry of Education, University and Research (MIUR). VISAS aimed to improve the responsible and sustainable exploitation of underwater archaeological sites through the development of three services. The first concerns the 3-D reconstruction of the underwater environment by using a methodology for optical and acoustic bathymetric data fusion. The second is based on a virtual reality system for dive session planning and 3-D exploration of the underwater site. Finally, the third service is intended to enrich the diving experience through a virtual guide running on an underwater tablet equipped with a hybrid tracking system.

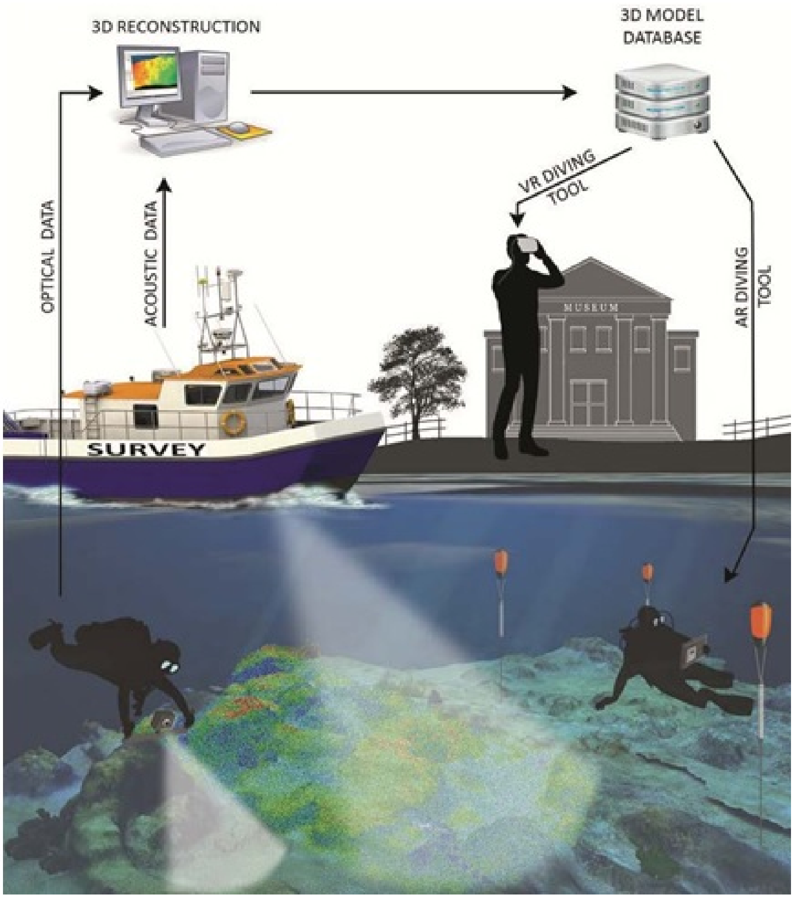

Figure 1: VISAS Architecture

The goal of the VISAS project was to build a low-cost underwater positioning and orientation system composed by one or more fixed beacons placed on the seabed and an underwater tablet equipped with an acousticmodem (LBL technique; see Figure 2). To improve the accuracy and increase the robustness in the case of loss of signal from one or more beacons, the tablet is also equipped with an inertial platform and a depth sensor. The data coming from the various sensors are processed through data fusion and error estimation algorithms. The tracking system on the tablet sends a query cyclically to each beacon and computes the distance from each of them measuring the two-way travel time (TWTT). These data are used by the data fusion algorithm to correct the estimate on the position obtained through the inertial system and the pressure sensor. The navigation software receives this information and shows the location of the tablet on a 3-D map of the underwater archaeological site.

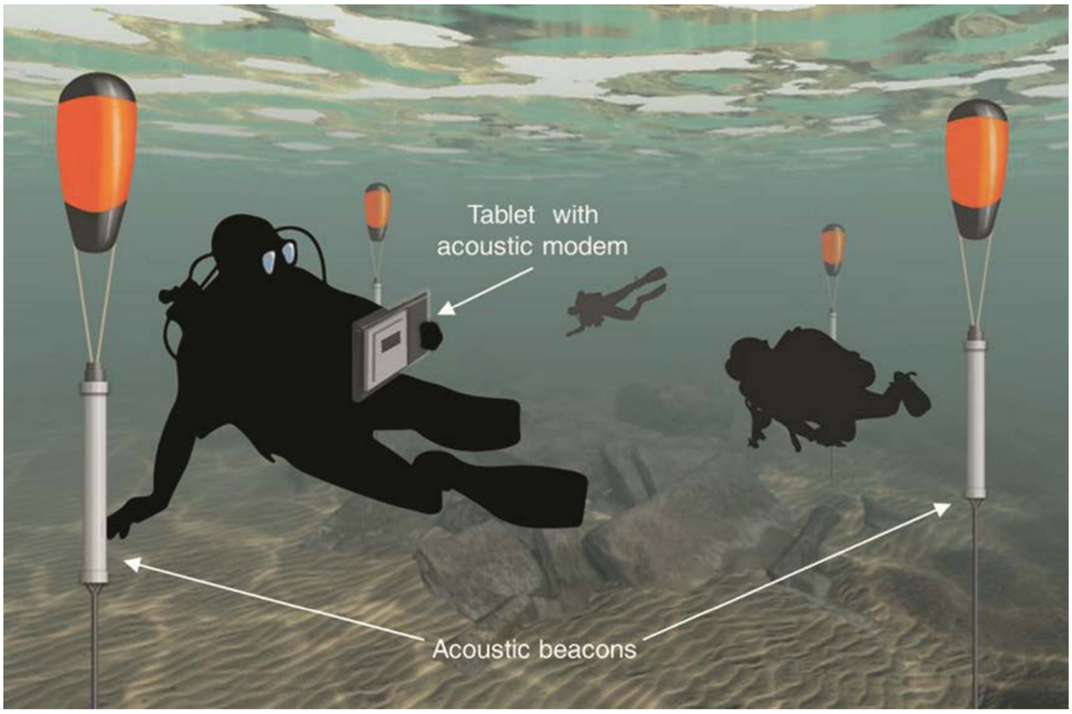

Figure 2: VISAS positioning system

2.3 Beacon

Each beacon contains an electronic board to drive the piezoelectric transducer (Figure 3). It operates in the 25- to 30-KHz frequency band, which is greater than the audible band (0– 20 kHz) to avoid annoying sounds to be perceived by the divers during the immersion. The beacon is equipped with a battery pack, which enables up to 5 h of use, and with anchor rings used to fix it on the buoy cable. The beacons are positioned at known geographical points using a mooring post and a surface buoy that facilitates their recovery.

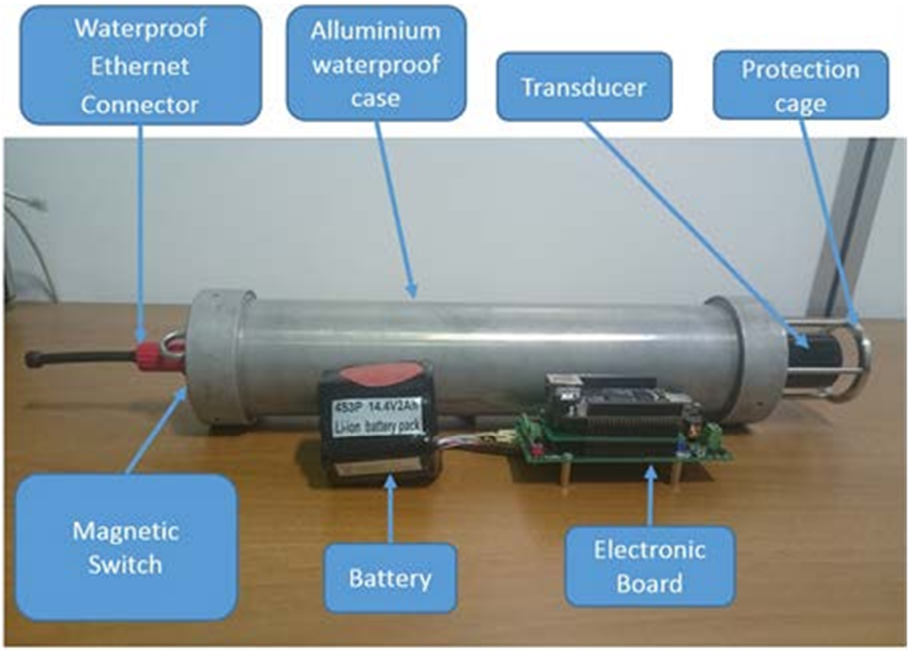

Figure 3: VISAS Beacon

2.4 Tablet

The tablet is composed of two major parts: a fully functional underwater touchscreen housing and a waterproof case for the electronics of the tracking system (Figure 4). The two devices are connected using a Wi-Fi interface. The tablet updates the diver's position on the 3-D map at a frequency of 50 Hz via the UDP protocol. The current position is estimated through an extended Kalman filter that uses the distances from each beacon, the depth provided by a pressure sensor, the accelerations along the three axes (x, y, z), and the orientations provided by an inertial platform (Figure 5). To compute the distance between the tablet and a beacon, the simplest way is to compute the time-of-fly of the acoustic wave. To this end, the acoustic modem on the tablet sends a two-way range (TWR) request to the remote beacon and starts an internal timer. Timer counts the time elapsed between the time of transmission and the time of reception of the corresponding response packet transmitted by the destination beacon. In this way, subtracting the fixed waiting time of the destination beacon and the CPU processing time required to decode the response packet, modem can accurately calculate the TWTT. The positioning system sends cyclically a TWR to all beacons. The tablet position is calculated within the Kalman filter by using a trilateration algorithm. Figure 6 shows electronic connections between devices in tablet case.

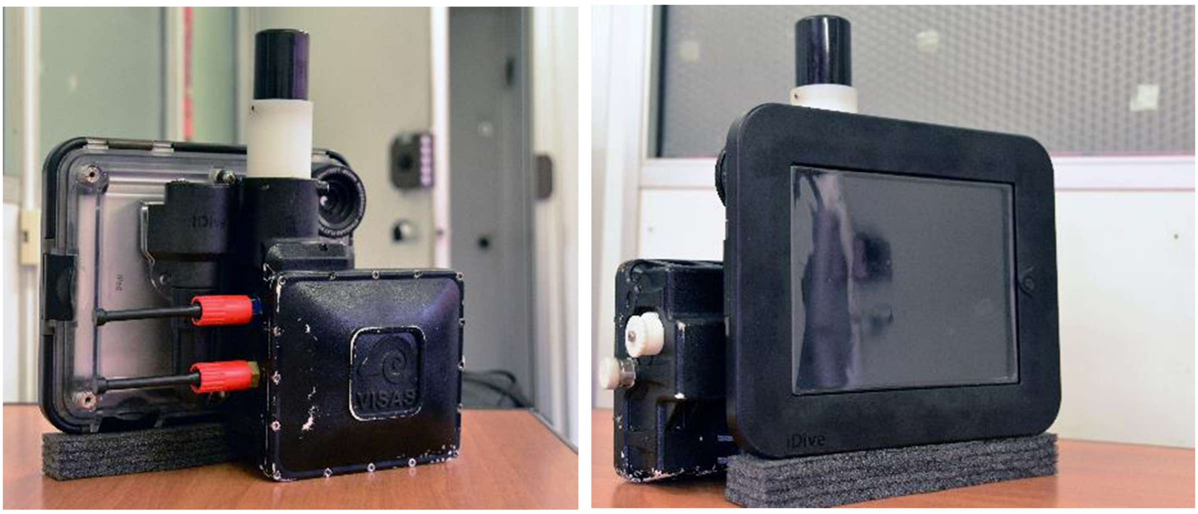

Figure 4: VISAS Tablet, Rear and Front views

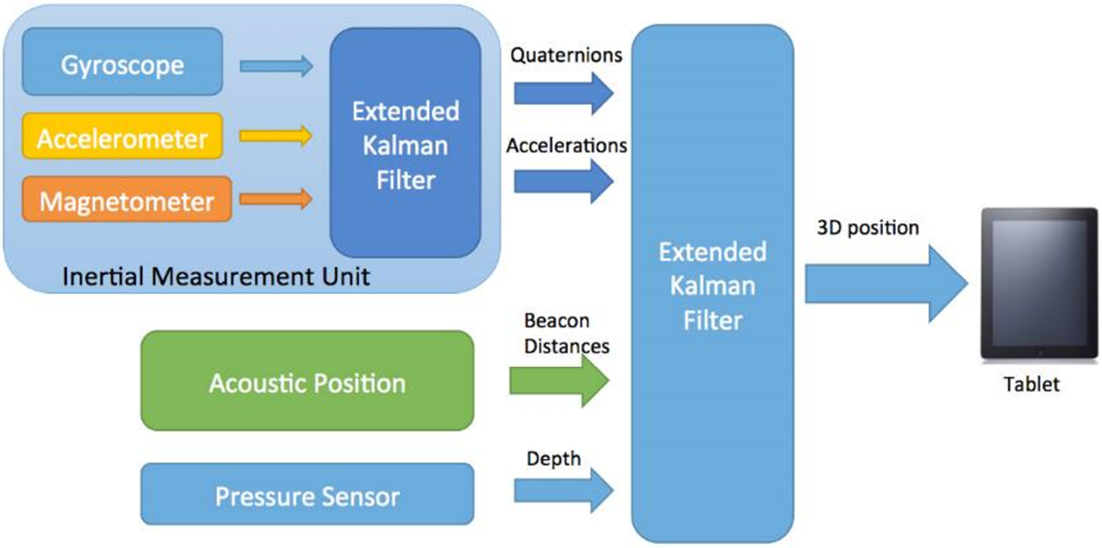

Figure 5: VISAS diver position estimation

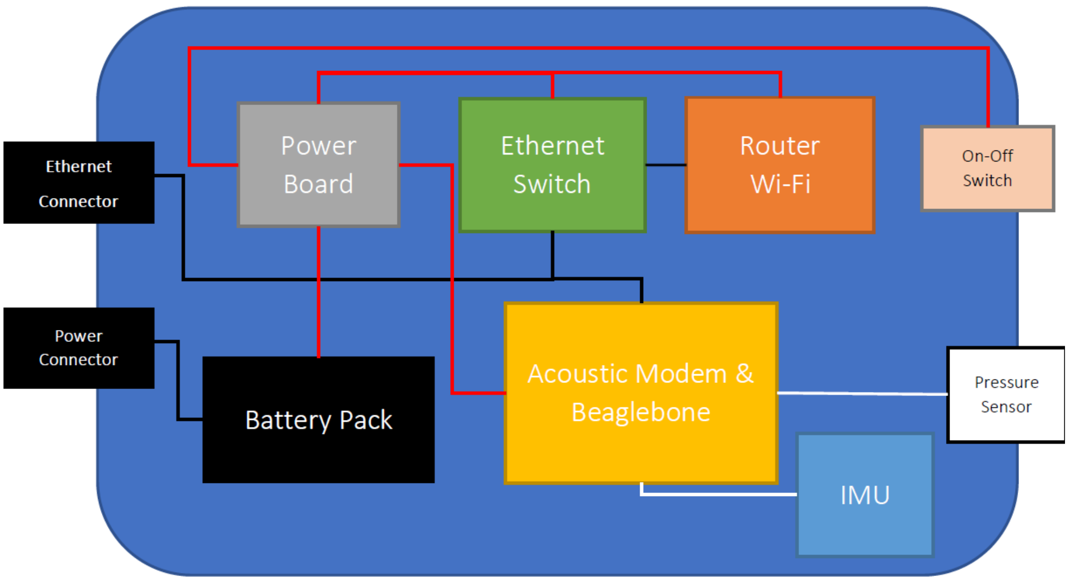

Figure 6: Tablet electronic schematic

3. BLUEMED Underwater Positioning System

The BLUEMED project, unlike VISAS project, involves the use of more than one tablet within the same underwater archaeological area for augmented exploitation. In order to achieve the BLUEMED project goals, it is necessary to customize and configure the positioning system in a different way than the one used in the VISAS project. The best solution in this scenario is a SBL localization system. The SBL positioning system has many advantages. First of all, the SBL, as previously described, can be mounted on the underside of a ship, small surface vehicle or a floating buoy. In fact, it can be simply deployed from the surface and doesn't require divers to install the transponder on the seabed as in the LBL system. The main drawback in LBL-like positioning systems (also in VISAS positioning system) is the long time and effort needed to calibrate and install the transponders. Moreover, the SBL installed near the surface can use a GPS to get its position and a precise timing signal, so that there is no need to precisely geo-reference each single transponder. Furthermore, any number of receivers can estimate their position in the same area if all the components of the SBL system are synchronized in time and one-way ranging protocols are used. In fact, the relative distances among beacons and divers can be estimated either measuring the two-way travel time (TWTT) or one-way travel time (OWTT) of the acoustic signal. Even if the advantage of the first method is that no absolute precision clock is required for the time travel measurement, TWTT does not scale well as the number of tablets involved in the ranging process increases. Instead, the OWTT approach scales perfectly with any number of divers as all tablets can get ranging updates at the same time. In fact, all tablets able to measure the OWTT can estimate their relative distances with respect to the sender without replying with any acoustic signal thus reducing the overhead of the network. The main drawback of this approach is that the clocks of the involved nodes have to be synchronized for the whole duration of the mission. While it might be easy to use GPS time on beacons that allow synchronization with each other without drift, it is much harder on the underwater tablet. In fact, the standard real time clocks integrated in the embedded platforms have high clock drifts and lose synchronization after a few minutes. Then, even if the integrated clocks are synchronized out of the water with the GPS, once in water the synchronization is lost after a short time. As a remedy, high precision clocks have to be used to estimate the OWTT, such as Chip Scale Atomic Clocks (CSACs) [2] that have a negligible drift over long periods of time or other kinds of highly accurate external clocks.

3.1 LBL Customization Schema

Starting from the system developed in the VISAS project, two possible SBL configurations will be considered. Notice also, as described previously,this system can be mounted on a buoy or on a vehicle.

3.1.1 Configuration #1

In this configuration, the beacons instead of being positioned according to a classic LBL schema are positioned as shown in Figure 9, in a SBL configuration.

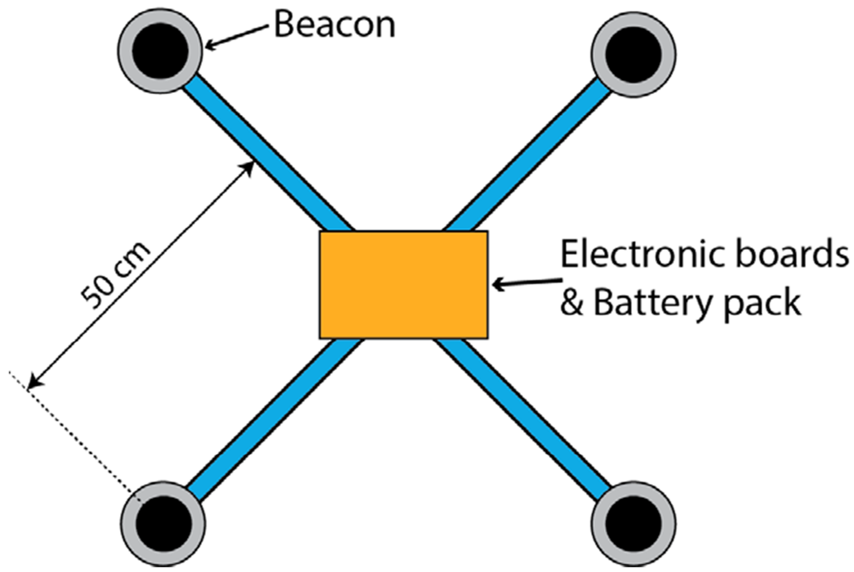

Figure 7: LBL customization - Configuration #1

In particular, the beacons are positioned on the vertices of one-meter long rods forming a X configuration. Electronics board and battery pack are positioned at the center of the bars in a suitable waterproof case.

Figure 10 shows electronic boards and battery pack connection schema.

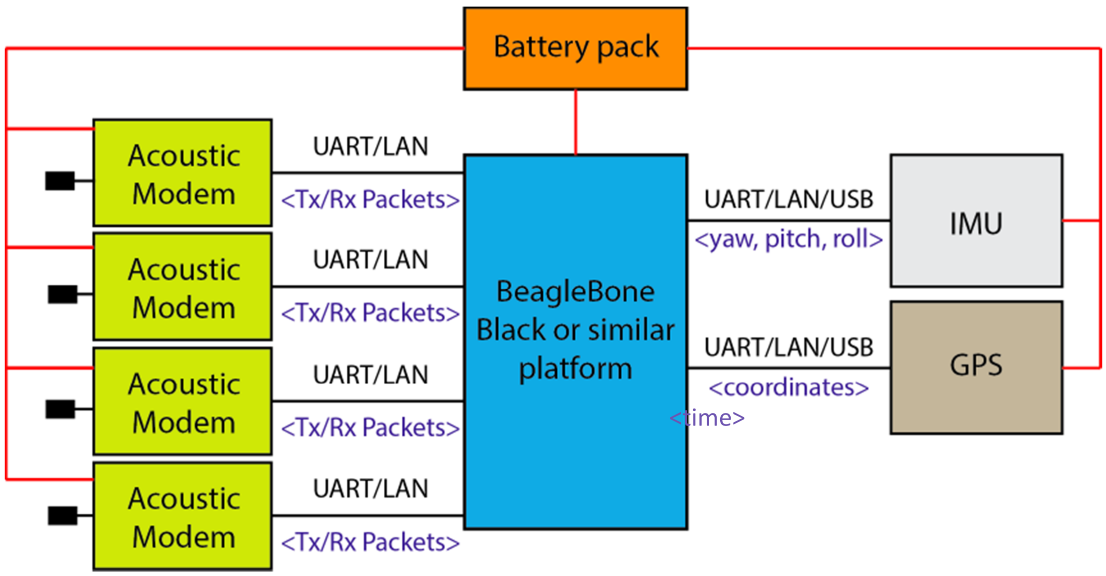

Figure 8: Electronic connection schematic – configuration #1

This configuration includes four acoustic modems, like those used in the beacons. A central platform (Beaglebone Black or similar) manages the transmission from each of them, cyclically sending the one-way range packets to the tablets. Packets sent to the tablets must contain (Figure 11):

- the ID of the transmitting beacon
- the transmission time
- the coordinates of the transmitting beacon

Beacon ID	Transmission Time	Beacon Coordinates

Figure 9: One-way range packet payload – configuration #1

The platform must then calculate, using appropriate trigonometric calculations, the position of the individual beacons using GPS position and the Euler angles from the IMU. Moreover, it must ensure that each modem is synchronized correctly with the GPS time.

3.1.2 Configuration #2

In this configuration, four transducers driven by the same modem will be used instead of the four modems of the Configuration 1. Transducers are positioned along the vertices of one-meter long rods forming a X configuration as configuration #1 (Figure 12).

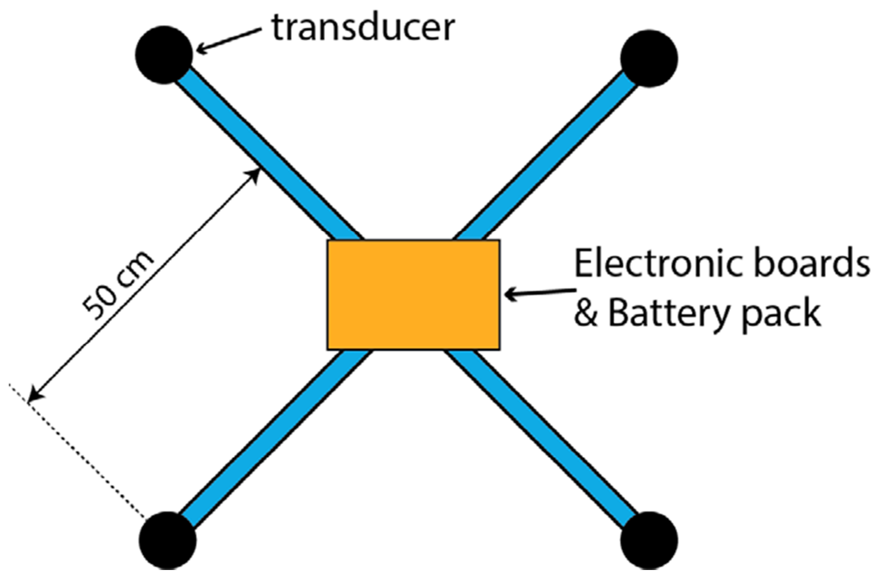

Figure 10: LBL customization - Configuration #2

The use of a single modem allows one to optimize space and reduce costs. On the other hand, the redundancy provided by the configuration #1 is lost (even in case of failure of one of the modem the overall system continues to operate). Furthermore, the synchronization of a single modem with GPS time must be managed instead of four modems in the configuration #2.

Figure 13 shows electronic boards and battery pack connection schema.

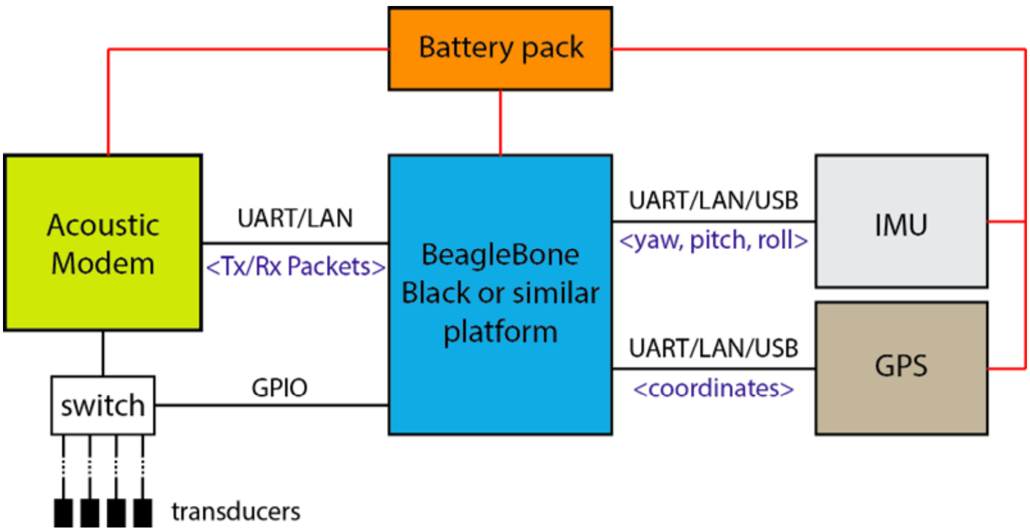

Figure 11: Electronic connection schematic – configuration #2

In addition to the single acoustic modem, this configuration provides an additional electronic board that allows the switching between the transducers. The central platform has to schedule the transmission from each transducer switching via GPIO the acoustic signal to the correct transducer. Packets sent to the tablets must contain:

- the ID of the transmitting transducer
- the transmission time
- the coordinates of the transmitting transducer

Transducer ID	Transmission Time	Transducer Coordinates

Figure 12: One-way range packet payload – configuration #2

As in the configuration #1, the platform must calculate position of each transducer and manage the modem clock synchronization with GPS time.

3.1.3 Tablet Customization

The electronics inside of the tablet case will be equal to that used in the VISAS project, except for the external clock that will be added to provide clock synchronization (Figure 15). The GPS antenna of the clock will be positioned inside the case or outside if the reception of the satellites will not be fine.

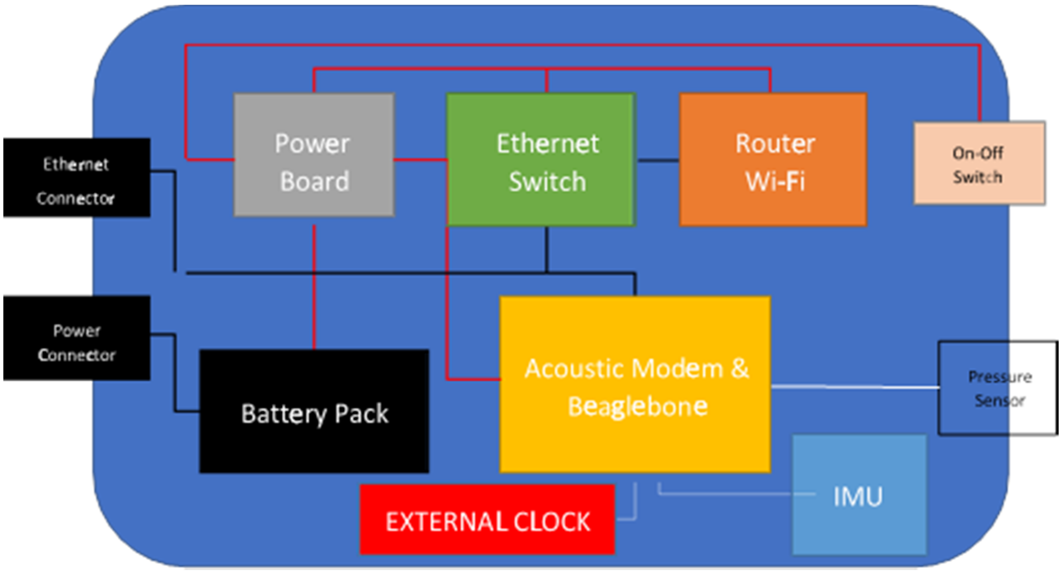

Figure 13: Tablet customization

The tablet software must be modified in order to take into account the one-way ranging schema provided by the LBL customization. Software updates will concern:

- software integration of external clock;
- range calculation from each beacon/transducer via a one-way range protocol;
- diver position calculation considering that the beacon position isn't fixed but is updated after each packet is received.

3.2 SBL Clock Synchronization

One-way ranging estimation can be successfully performed only if the clocks of the involved nodes (tablets and beacons) are synchronized and the receiving nodes know exactly the actual starting transmission time of the received packet. This information is contained in the header of the one-way ranging packets sent alternately by each beacon. All the tablets that receive the one-way ranging packet are therefore able to estimate the relative distance with the sender by using the time of packet reception provided by the acoustic modem on board, the transmission time contained in the packet and the value of the sound speed. The one-way ranging can be performed on single or multiple destination tablets, simultaneously. Only one broadcast packet is needed for all neighboring tablets to be able to estimate the distance from the sender.

In order to calculate the position of the diver, beacons send alternately a one-way ranging packet to the tablets. The tablet that will receive the packets will be able to calculate the distance from any beacons and estimate, through Extended Kalman Filter, its position within the archaeological site such as done by the VISAS positioning system. If the positions of the beacons are fixed their value may be set in the initial parameters of the system, otherwise, if the system is mounted on a buoy or on a vehicle, the position of the transmitting beacon must be contained in the one-way ranging packet.

3.3 SBL External Clock

On the market there are many different solutions that can be used to maintain clock synchronization during an archeological underwater exploration. Mainly they differ on the technology used inside the oscillator to update the internal clock. The most advanced and costly solution on the market is the chip scale atomic clock that provides the accuracy and stability of an atomic clock in a small chip scale package. Other cheaper solutions use instead OCXO (Oven Controlled Crystal Oscillator), VCXO (Voltage Controlled Crystal Oscillator) or TCXO (Temperature Controlled Crystal Oscillator). As described in the following table, reducing the cost reduces also the accuracy and increases the time drift.

Oscillator Type	Accuracy	Cost
TCXO	10^{-5}	Inexpensive
VCXO	10^{-7}	5€ - 200€
OCXO	10^{-8}	50-500€
CSAC	10^{-10}	2.500€

According to the previous Table, two possible solutions can be used as external clock inside the BLUEMED SBL positioning system.

The CSAC Microsemi Quantum SA.45s (Figure 7) is the world's first commercially available chip scale atomic clock, providing the accuracy and stability of atomic clock technology while achieving true breakthroughs in reduced size, weight and power consumption lower than 120 mW. The CSAC produces two outputs, a 10 MHz square wave and 1 Pulse Per Second (PPS), both at standard CMOS levels, with short-term stability (Allan Deviation) of 2.5e −10 at TAU = 1 s, long term aging lower than 9e −10 per month, and maximum frequency change of 5**e −**10 over an operating temperature range of 10 ◦C to 35 ◦C. It also accepts a 1 PPS input that may be used to synchronize the unit's 1 PPS output to an external reference clock up to 10 ns of accuracy (cabled synchronization), like a GPS or another CSAC, and provides an RS-232 interface for

Figure 14: Microsem CSAC SA.45

monitoring and control. Some good results using CSAC were achieved in [3] where it was shown that the use of CSACs allows one to overcome the typical clock drifts of the standard real-time clocks thus makingfeasible one-way range estimation for long term missions. The main problems using this type of external clock is the high cost of the CSAC (around 2.5k €) and its maximum operating temperature (35 ◦C) after which the chip can be damaged permanently even if turned off.

The ***Microsemi GPS-1000*** (Figure 8) is a 10 MHz OCXO-based (Oven Controlled Crystal Oscillator) GPS Disciplined Oscillator (GPSDO), covering an operating temperature range of 0 °C to +60 °C. The unit features a high-performance GPS receiver that can track up to 50 GPS signals, down to levels as low as -160 dBm. The receiver is compatible with GPS, WAAS, EGNOS, and MSAS signals, and is Galileo-ready. The output signal is a 10 MHz sine wave and also it provides a single 1 PPS output CMOS compatible. The 1 PPS output has an accuracy of +-

50 ns to UTC RMS, once GPS lock has been achieved. Because of its small size and because the GPS-1000 uses an evacuated single-oven OXCO as its holdover oscillator, it can warm up in < 1 min at +25 °C. Holdover stability is +- 11usec over 3 hour period at 25 °C with no motion and the unit typically consumes < 1.4W of power at +25°C.

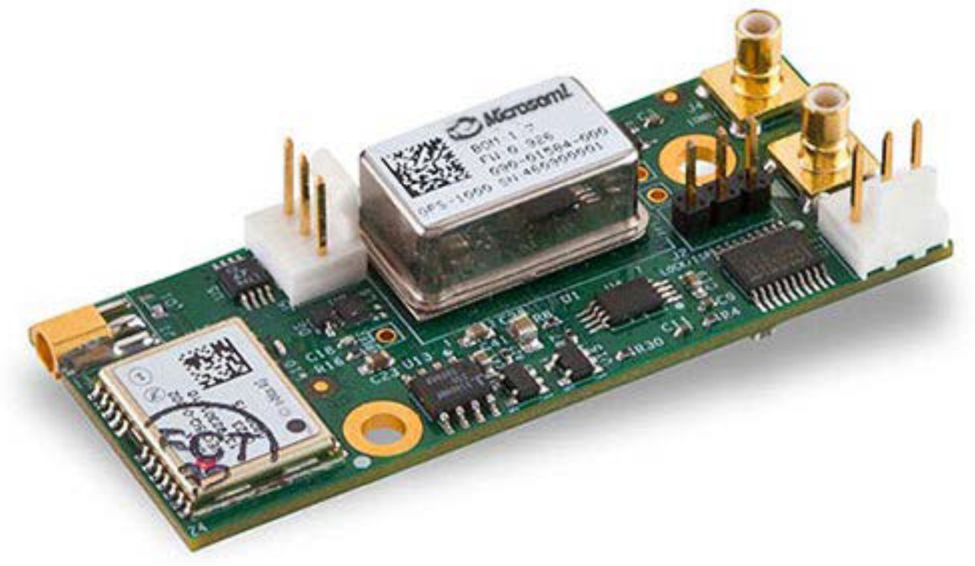

Figure 15: Microsemi GPS 1000

Other manufacturers offer similar products at similar price (500 to 1000 €), and, considering the lower cost and automatic synchronization with the GPS time, these clocks are an ideal solution for use on tablets to achieve the project goals.

3.4 PlaDyPos Integration

The ASV platform PlaDyPos [4] was developed at the University of Zagreb Faculty of Electrical Engineering and Computing, at the Laboratory for Underwater Systems and Technologies (LABUST). The Pladypos is over-actuated with 4 thrusters forming an X configuration. This configuration enables motion in the horizontal plane in any direction.

Figure 16 shows possible integration of customized LBL in configuration #2 with PlaDyPos. In this case, the data (coordinate, Euler angles, GPS time) are sent directly from the vehicle to the positioning system via Ethernet connection. In order to follow from the surface the master diver, the latter sends its position to the vehicle in the dead time in which the positioning system is not transmitting.

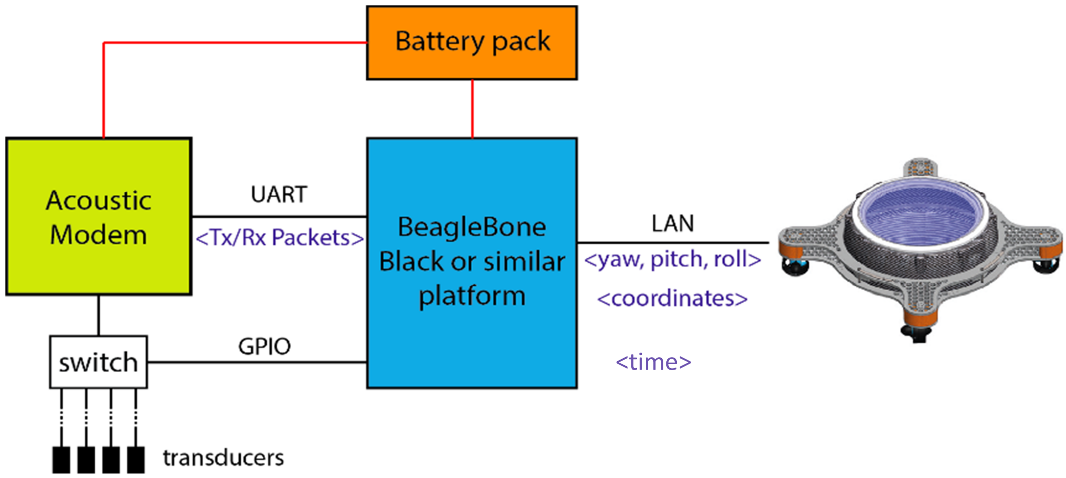

Figure 16: PlaDyPos Integration

3.4.1 PlaDyPos – Positioning System communication Protocol

Messages passing between the vehicle and the positioning system (PS) will be through TCP/UDP protocol. The communication protocol involves the use of a TCP socket dedicated to send commands to the PS, an UDP socket in which the GPS and IMU data are transmitted from the vehicle to the PS and an UDP socket in which current master diver position is transmitted from the SBL to the vehicle.

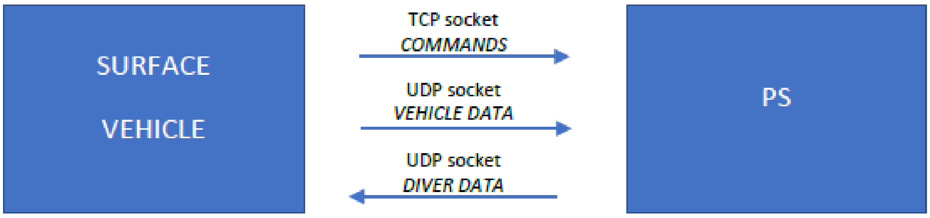

Figure 17: PladyPos - PS communication protocol

Through the TCP channel the vehicle is able to:

- start and stop the acoustic location service
- act on the PS configuration parameters for the tuning of the positioning system

Through the UDP channel the vehicle is able to:

- receive from the PS the master diver coordinate (latitude, longitude, depth)
- send to the PS its current GPS position (latitude, longitude) and IMU data (yaw, pitch, roll) so that PS can calculate the current position of each transducer

4. References

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