Mobile Submarine Target Strength Measurement*

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ABSTRACT

A methodology is proposed for the measurement of submarine target strength whilst in transit, utilising submarine navigation systems and sonobuoys. Direct sequence spread spectrum signals are transmitted via VHF to a telemetry relay sonobuoy, which re-transmits the signal acoustically. A standard sonobuoy receives the signal and relays it to the data recorder. Using high stability clocks for the synchronisation of the transmitter and receiver, accurate time-of-flight measurements can be made between sonobuoy transmitters and receivers via direct and reflected acoustic paths. The positions of the three objects need to be known to discriminate between target and surface reflections and to measure the bistatic angle between the source, target and receiver. The positions of the target are estimated by the submarines inertial navigation system, and the positions of the other objects are estimated using the submarine position as a reference, and constructing a baseline over time as the submarine moves. Target strength is calculated by comparing the correlation of the signals received from the direct path and reflected paths, with reference signals. This technique enables target strength measurements in negative SNR environments. The implementation of this methodology is described and the results of a simulation of an operational scenario are presented.

INTRODUCTION

Various methods and systems exist for the measurement of the radiated noise of submarines. These systems help build an understanding of the submarines vulnerability to passive sonar. To date, there is no convenient method for measuring a submarine's vulnerability to active sonar. Active sonar, particularly with bistatic geometry, is a very effective tool for locating an uncooperative submarine. Knowledge about the vulnerability of a submarine to active sonar is useful for submariners in determining the likelihood of being 'seen' by an active sonar pulse. Target strength is part of the active sonar equation which is required for the estimation of active sonar detection ranges.

The target strength (TS) of a body is a measure of it's reflectivity from a plane wave; it is usually expressed the ratio of reflected intensity to the incident intensity.

$$TS = 10\log_{10}\frac{I_r}{I_i} \tag{1}$$

Where I_r is the reflected intensity

I_i is the incident intensity

The intensity of the reflected and incident signals vary with time, and there are various methodologies which may be used to measure the intensities. The method used here is integrated target strength, where the incident and reflected intensities are measured by integrating over the duration of the pulse signal and echo (Jones & Clarke, 2000).

$$TS_{Integrated} = 10\log\frac{\int_0^{t_r} p_r^2\, dt}{\int_0^{t_i} p_i^2\, dt} \tag{2}$$

Active Sonar Equation

Target strength is not directly measurable; it must be derived from the received levels from an ensonifying source, the received levels from reflections from the target, and estimations of the ranges between each of the objects.

The components that contribute to the received level from a reflected pulse, in the absence of noise, can be simplified to the following form of the active sonar equation

$$RL = SL - TL_1 + TS - TL_2 \tag{3}$$

Where RL is the received level of the echo return,

SL is the source level,

TL_1 is the transmission loss from the source to the target,

TL_2 is the transmission loss from the target to the receiver

Rearranging (3) for target strength leaves the quantities of RL, SL, TL_1 and TL_2 as measurable inputs.

$$TS = RL - SL + TL_1 + TL_2 \tag{4}$$

Note that SL is the range corrected received level of the direct signal.

i.e. $$TS = RL_r - (RL_i + TL_3) + TL_1 + TL_2 \tag{5}$$

Where RL_i is the received level from the incident pulse

TL_3 is the transmission loss between the source and the receiver.

Estimation of the transmission loss between the source and the target and between the target and the receiver requires accurate measurement of the ranges between the three objects (for bistatic geometry).

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Target strength measurement also requires the discrimination of those signals which are reflections from the target, and those which are reflections from other boundaries. These uncertainties can be removed (for all except the most ambiguous geometry) if the positions of all the objects is estimated in the process.

In the case where the signal to noise ratio of the reflected pulse is very high the integrated target strength can be estimated by comparing the time series of the incident and reflected pulses. It is reasonable to assume that the SNR of the reflected pulse may be very low in some cases, so some signal processing must be applied in order to make repeatable target strength measurements.

TARGET STRENGTH ESTIMATION

If the shape of the signal pulse is precisely known, the relative levels of RL_i and RL_r can be measured by cross correlating the incident and reflected signals with a reference signal. This method has the advantage of;

- Automatically locating the start time and the duration of the incident pulse and a single echo. The correlation process is repeated over a range of Doppler estimates to maximise the match between signal and replica pulses. This in effect maximises the likelihood of the encapsulation of the entire pulse duration.
- Producing a processing gain to enhance the ability to measure target echoes in low SNR environments

Consider a normalised reference signal, $A_0 s(t)$, the received incident pulse $A_1 s(t)+\sigma_1(t)$ and the received reflected pulse $A_2 s(t)+\sigma_2(t)$, where σ is the in-band noise component.

The cross correlation of the incident pulse with the replica signal may be written as

$$A_0 s(t) * A_1 s(t)+\sigma_1(t) = \int_{-\infty}^{\infty} A_0 s(-\tau)\left(A_1 s(t-\tau)+\sigma_1(\tau)\right)d\tau = \int_{-\infty}^{\infty} A_0 s(\tau)\left(A_1 s(t+\tau)+\sigma_1(\tau)\right)d\tau \qquad (6)$$

(Weisstein, 2005)

Where * denotes correlation and *s(t)* is real.

The maximum value for (6) is an estimate of the expected total signal energy (if $A_0 s(t)$ is normalised) and occurs when t = 0. This correlation peak contains a noise component equal to the inner product of the replica signal and input noise. At t = 0, the expected value of the correlation peak is

$$\langle E_i \rangle = \int_{-\infty}^{\infty} A_0 A_1 s^2(\tau) + A_0 s(\tau)\sigma_1(\tau)d\tau \qquad (7)$$

If *s(t)* is a Pulse Amplitude Modulated (PAM) signal modulated by a pseudo random number sequence whose duration is τ , then $s^2(t)=1$ for all values of *t* and the expected value of the correlation peak for the incident pulse is

$$\langle E_i \rangle = A_0 A_1 \tau + \sum_{k=0}^{\tau-1} A_0 s_{kt} \sigma_{1k} \qquad (8)$$

And the ratio of the two correlation peaks is then

$$\frac{\langle E_r \rangle}{\langle E_i \rangle} = \frac{A_0 A_2 \tau + \sum_{k=0}^{\tau-1} A_0 s_k \sigma_{2k}}{A_0 A_1 \tau + \sum_{k=0}^{\tau-1} A_0 s_k \sigma_{1k}} \qquad (9)$$

Comparison with time series measurement

The ratio of the direct measurement of the time series amplitude of the incident and reflected signal amplitudes in the presence of noise can be expressed as

$$\frac{\langle E'_r \rangle}{\langle E'_i \rangle} = \frac{A_2 + \sigma_2}{A_1 + \sigma_1} \qquad (10)$$

In the absence of noise, (9) and (10) are identical.

Recall that in (7), *s(t)* is PAM signal, modulated by a pseudo random number sequence. Consequently the inner product of $A_0 s$ and σ is of similar magnitude to the sum of the components contributing to σ, since $A_0 s$ is normalised. However, the signal amplitudes (A_1 and A_2) are each scaled by the length τ of the signal, thus increasing the 'signal' amplitude over the 'noise' amplitude by the processing gain, which is equal to the length τ (in chips).

The ratio of the correlations of the incident and the reflected pulses has been shown to be equal to the ratio of reflected and incident received time series amplitudes in the absence of noise, and a more accurate measurement than using the time series amplitude measurement if the signal to noise ratio is low. Relating back to the active sonar equation,

$$RL_r - RL_i = 20\log_{10}\left(\frac{\langle E_r \rangle}{\langle E_i \rangle}\right) \qquad (11)$$

Transmission Loss Estimation

To complete the active sonar equation, the three transmission loss values need to be calculated. A spherical spreading model is practical and adequate for the short ranges (< 300 m) and short pulse lengths to be used in the operational scenario. Transmission paths are expected to be close to straight, and the multipath arrivals will appear as additional correlation peaks that will not influence the signal level estimation if sufficiently precise time gating is enforced. To this end, time-of-flight measurements between source and receiver, source and target, and target and receiver must be measured with sufficient accuracy to discriminate between the correlation peaks from target reflections and those from surface and bottom reflections.

TARGET STRENGTH MEASUREMENT OPERATIONAL SCENARIO

Sources & Receivers

Standard SSQ53F ANM Sonobuoys or their equivalent have been chosen as receivers. The acoustic bandwidth of the SSQ53F when used in omni mode is 10 Hz to 20 kHz. Signals have been received much higher than 20 kHz with SSQ57 Sonobuoys, the predecessors to SSQ53F, although a 6 dB /octave roll off occurs after 20 kHz. (Warriner & Ghiotto, 2002). The dynamic range is approximately 65 dB, and the equivalent electronic noise floor is typically close to sea state zero (Production Sonobuoy Spec., 1998). Acoustic signals are relayed via VHF FM radio to the PASOR receiver, which records continuously.

A new type of sonobuoy, the Acoustic Telemetry Buoy (ATB), may be used as an acoustic source. This sonobuoy demodulates VHF AM radio signals and relays them as acoustic signals. The maximum SPL output of the ATB is 180 dB, and it has an operational frequency band of 15 kHz to 25 kHz (Souto, 2003). This frequency band is comparable to the active sonar band of some anti-submarine weapons.

Proposed Trials Geometry

The ATB (source) and ATB (receiver) sonobuoys can be laid in an arbitrary pattern, depending on the bistatic angles of interest. The pattern shown in Figure 1 enables a range of bistatic angles for each run.

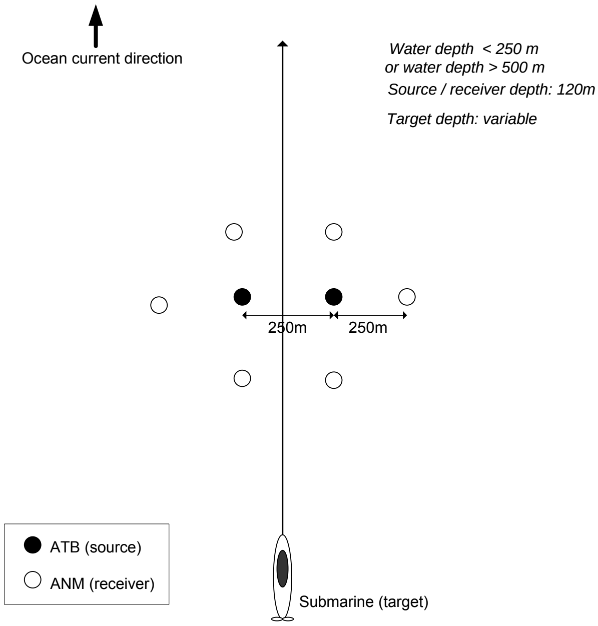

Figure 1 - Trials geometry

For simplicity, the target moves in a straight line through the sonobuoy field, and for ease of navigation, the sonobuoys are separated by a distance of approximately 250 m.

The trials geometry should be chosen carefully to avoid the convolution of boundary reflected signals with target echoes. In the geometry suggested in Figure 1, water depths between 250 m and 500 m should be avoided because at these depths the convolution of boundary reflected signals and target echoes will occur, as illustrated in Figure 2.

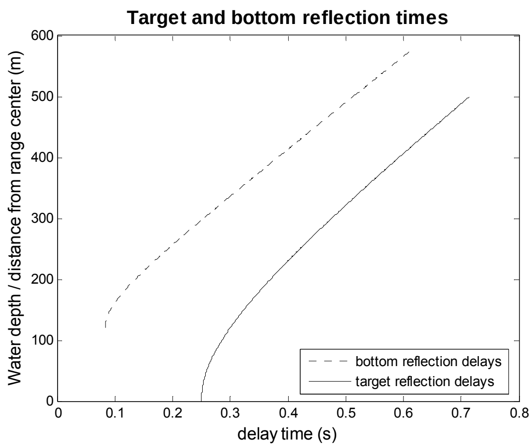

Figure 2 - Target and bottom reflection delay times

Figure 2 shows the delay times for target reflections and bottom reflections, for all objects at 120 m depth. Surface reflection delay times are equivalent to bottom reflections for a water depth of 240 m.

EXISTING INFRASTRUCTURE

The methodology described herein relies on the use of an existing passive noise measurement system; the Portable Acoustic Sonobuoy Ranging (PASOR) system, developed by Nautronix Ltd. PASOR solves some of the problems of range measurement, target and receiver position estimation, target orientation, and received level measurement and data recording.

The PASOR system requires five beacons to be distributed about the submarine. These beacons continuously emit periodic band-limited direct sequence spread spectrum signals, which are relayed to the PASOR Data Acquisition System (DAS) via standard ANM sonobuoys. The DAS and the computer that generates the beacon signals, the Submarine Tracking System (STS) are slaved to high stability (rubidium) clocks, synchronized to GPS, so that accurate time-of-flight measurements can be made between the beacons and the sonobuoy acoustic elements. Other contributors to the times of flight are the EM wave propagation and radio receiver hardware but these accumulate to a tiny sum, less than the uncertainty of the time-of-flight measurements, which is ±100 µs.

Spectrum allocation and source levels

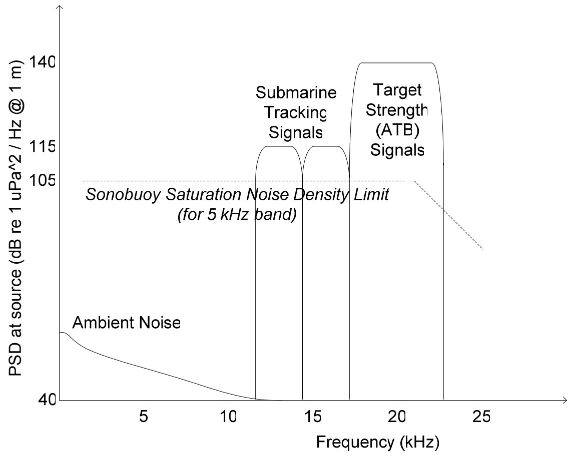

Figure 3 - Spectrum allocation and source levels

Figure 3 shows the frequency and source level of the signals required for the target strength measurements. Sonobuoy saturation levels for narrowband signals are approximately 37 dB higher than shown in Figure 3. The range between the ATB and the ANM sonobuoy receivers should always be greater than 100 m to avoid saturation of the sonobuoy electronics.

SIGNAL CHARACTERISTICS

Target Strength measurements are commonly made using impulsive sources, such as explosives or the cavities made by airgun or evacuated sphere sources. Alternatively signals that have been precisely synthesised, and hence with known characteristics can be detected when the (incoherent) SNR is very low or even negative, by using the methods described above. If signals are time synchronised, as in the case of the signals projected by the submarine tracking system beacons, then time-of-flight measurements can be made between the source and the receiver.

The period of the signals must be short in order to minimise the overlap of direct and surface reflected signals with the target reflected signals. Similarly, the source level must be sufficiently high to enable a measurable target echo, but not too high as to saturate the limited sonobuoy receiver dynamic range.

Band limiting is necessary in order to minimise the mutual interference between the STS and Target Strength analysis systems. Band limiting the DSSS signals prior to modulation removes the need for filtering the signals on output and simplifies the time synchronisation process.

The signals are synthesized using only the required Fourier components of the base-band signal and then modulating with the sine wave carrier. A summary of the signal generation, as detailed by Cook (2000) follows;

A pulse amplitude modulated (PAM) waveform modulated by a bipolar binary pseudo random number (PRN) sequence with length *L,* is generated:

$$u(t) = \sum_{-\infty}^{\infty} m_k g(t - kT_{ch}) \tag{12}$$

where m_k is the value of the k_{th} chip in the PRN sequence, T_{ch} is the chipping period and *g(t)* is the rectangular pulse function:

$$g(t) = \begin{cases} 1 & 0 \le t < T_{ch} \\ 0 & \text{otherwise} \end{cases}$$

The Fourier series representation of *u(t)* is

$$u(t) = \sum_{n=-\infty}^{\infty} U_n e^{j2\pi f_0 t} \tag{13}$$

For a band limited signal, where only part of the main lobe is generated,

$$u(t) = \sum_{n=-k}^{k} U_n e^{j2\pi n f_0 t} \tag{14}$$

where $k = Ll$

and $l \le 1$, the fraction of the main lobe to be generated.

Since *u(t)* has Hermitian symmetry, we can sum over the real frequencies only; i.e.

$$u(t) = 2\Re \sum_{n=0}^{k} U_n e^{j2\pi f_0 t} \tag{15}$$

The fundamental frequency f_0 of the PAM waveform is

$$f_0 = \frac{f_{chip}}{L} \tag{16}$$

The Fourier coefficients U_n are

$$U_n = \frac{1}{L} \sum_{k=0}^{L} m_k \operatorname{sinc}\left(\frac{n}{L}\right) e^{-j\frac{2\pi n\left(k+\frac{1}{2}\right)}{L}} \tag{17}$$

Two signals $u_1(t)$ (in phase) and $u_2(t)$ (quadrature) are then modulated over a sine wave carrier

$$s(t) = u_1(t)\cos(2\pi f_c t) + u_2(t)\cos\left(2\pi f_c t + \frac{\pi}{2}\right) \tag{18}$$

where f_c is the carrier frequency

For the target strength signals, length *L* and the lobewidth *l* is chosen to produce a bandwidth of 5110 Hz and a sequence duration of 100 ms.

For the proposed geometry, in the worst case the time delay between the surface reflection and the target reflection is just over 100 ms. Therefore a signal length of 100 ms will eliminate the possibility of the overlap of reflections, except where the submarine has veered off track and too close to a sonobuoy.

Time-of-flight measurements from target to receivers

The target to receiver time-of-flight measurements are made by cross correlating the incoming STS signals with Doppler corrected replica signals, pre-calculated and stored on the PASOR system. The STS signals are transmitted continuously, with each signal *s(t)* transmitted at a τ GPS time boundary, where τ is now the sequence length in seconds. The cross-correlation is circular, and the boundary between transmitted signals is smooth so the correlation result for an incoming signal with arbitrary delay Δt with a replica signal will show the correlation peak shifted by Δt.

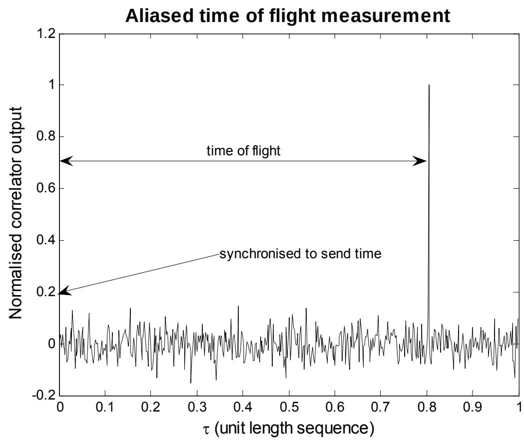

Figure 4 - Aliased time-of-flight measurement

The time-of-flight (aliased to τ) is the difference between the arrival time (i.e. the correlation peak time) and the most recent τ GPS boundary at the receiver. The time-of-flight measurements are synchronised (dealiased) by the periodic transmission of the GPS time at the transmitter (seconds only), packetised in the signal payload.

Time-of-flight measurements from source to receivers

The ATB signals used as the ensonifying source for target strength measurements differ from the STS signals in that they are pulsed and the STS signals are continuous. The ATB signals have a period of 100 ms and are transmitted once at each GPS second boundary. The direct and reflected pulses are located using the following methodology;

Incoming time series data is buffered into sections of convenient FFT lengths, overlapped by 50 % of the buffer length, or 50 % of the buffer length + 1 if the buffer length is odd. (The FFTW library performs very fast FFTs for FFT lengths that are the product of the powers of low primes, which may be odd). This overlapping ensures that the entire pulse will be encapsulated by one of the buffers.

The replica signals are zero padded to FFT length, and the correlation operation is performed for each section of (demodulated and band pass filtered) data, until a correlation peak exceeds the detection threshold. The time-of-flight is the time difference between the correlation peak and the most recent GPS second boundary.

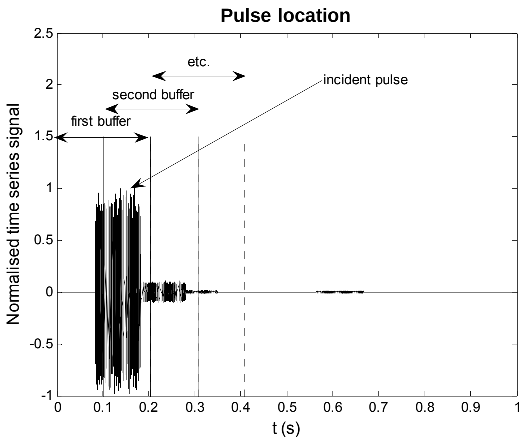

Figure 5 - Location of pulses in time series data

Ranges greater than ~1500 m will be aliased, but such long ranges are outside of the operational envelope of target strength measurement using the proposed system.

Position Estimation

The position of the target is estimated by the submarine's inertial navigation system and the current target position is a reference for all other position estimations. Target positions, heading and speed are telemetered to the data acquisition system in the payload of the beacon signals.

A Least Squares technique is used estimate the positions of the sonobuoy receivers, and these positions and the measurement residuals are used as inputs for a Kalman filter. The outputs of the Kalman filter are the positions and velocities of the sonobuoy receivers.

At any instance, a quasi-synchronous arrival of up to three time-of-flight messages between the target and each receiver is realised at the DAS. This allows for a unique solution in three dimensions. In order to provide a more robust, over determined solution, time-of-flight messages are collected over a period of a few seconds. The resolution of time-of-flight measurements is much finer (up to 150 x) than the resolution of the target position estimates, which are telemetered approximately once every 10 seconds. In order to set up a measurement equation for a history of time-of-flight measurements the target position must be interpolated over the time instances at which the time-of-flight messages are realised.

The position and velocity estimates of the sonobuoys are telemetered to the submarine after each pass through the sonobuoy field, via the ATBs. The sonobuoy positions and velocities are updated on a display on the submarine to facilitate submarine navigation through the sonobuoy field.

This leaves the problem of the position estimation of the acoustic source. The time-of-flight between the source and each receiver is measured by the method described above, and the ANM sonobuoy receivers form a baseline for the position estimation of the ATB source. Figure 6 shows the high level logic process for the calculation of the ATB positions.

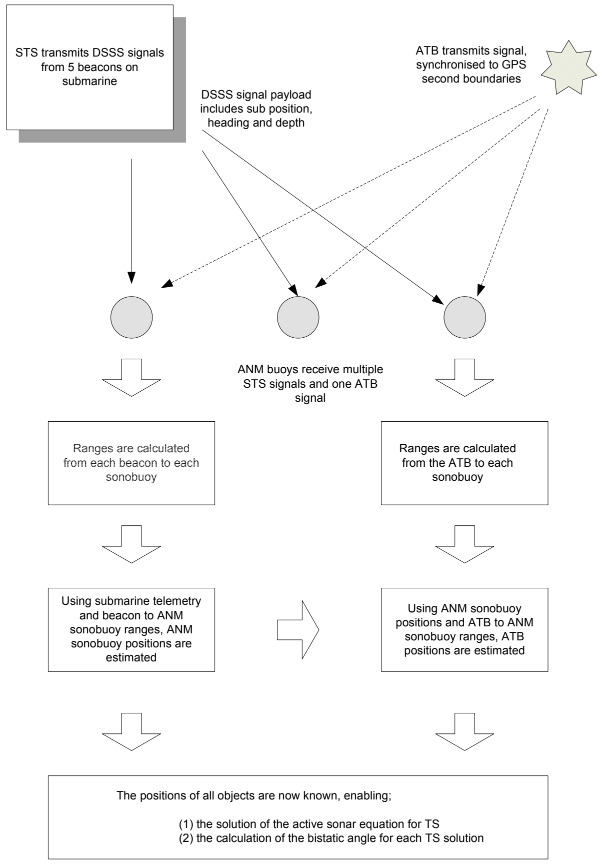

Figure 6 – ATB Position estimation

The ATB signals are received at multiple sonobuoys, the positions of which are dynamically estimated. Simulations have shown the ANM sonobuoy position estimates to have an rms accuracy of 3 m. The large spatial separation of the ANM sonobuoys provides a relatively long baseline and the ATB position estimation has been simulated with accuracy of < 5 m rms.

Figure 7 shows typical results of a simulation of ATB position estimation, where the ATB positions are calculated for at all times during a complete circuit of a submarine moving past the sonobuoy field at ~15 knots and making a looping Williamson turn at each end. The drift speed of the sonobuoys and ATB was 1 knot and their estimated positions had an rms accuracy of < 3 m.

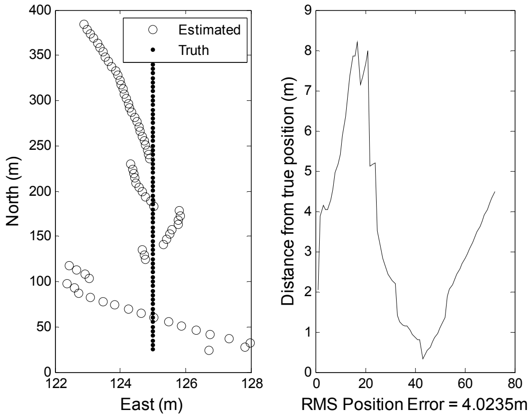

Figure 7 – Simulated ATB position estimation

With all positions known, the ranges between the source and the target can be estimated, completing the RHS of the active sonar equation for target strength.

Time Gating

The target returns must be separated from the returns from other boundaries, such as the sea surface. This can be done by time gating the received signals, if the relative positions of the three objects involved are known. The time gate should be long enough such that echoes from the entire length of the target are encapsulated, and uncertainty in source, target and receiver positions are accounted for. If a significant portion of the predicted temporal location of the target echo pulse coincides with the predicted temporal location of any boundary reflected pulses, the result should be discarded, as the target strength estimate is likely to be corrupted.

Estimating the uncertainty in propagation time

In the simulated scenario described above, the range measurement uncertainties are;

Target to receiver: The time-of-flight measurement between the target and receiver is measured directly. The resolution of the time-of-flight measurements is a function of the sequence length *L,* and more directly, the inverse FFT size in the correlation operation. In this case the IFFT has size 1024 points, and the length of each sequence is 0.2 seconds. So each FFT bin represents $\frac{200}{1024}$ ms, or ~200 µs.

Source to receiver: This is also a time-of-flight measurement with the same FFT size, but half the sequence period, so the time resolution is ~ 100 µs.

Source to target: This is not a direct time-of-flight measurement, but a distance calculation based on the submarine positions, which are telemetered to the observation platform, and the ATB positions, calculated in the observation platform. The positions of submarine and ATB will be synchronous to within the time resolution of the submarine combat system, as all telemetry data is sent on GPS second boundaries and forms the starting point for all other calculations. The accumulated error in position estimation of the submarine (due entirely to the time resolution, since the submarine position *is* the system reference) is a function of submarine speed. At the speed indicated in the simulation, the error in position is ≤ 3 m. The error in ATB position has been simulated as 4 m RMS, with a maximum of 8 m. Combining the two, the uncertainty in range is ±11 m, which translates to a time resolution of 14.7 ms at worst case.

The combined uncertainty in the propagation time for the reflected pulse is then

$$\varepsilon_{delay} = \pm\frac{14.7 + 0.2}{2} \approx \pm 7.5 \text{ ms.}$$

(For the simulation described)

Detecting the reflected pulses

The propagation time for the reflected pulse is calculated using the estimated positions of the source and the target, and the direct time-of-flight measurement between the target and the receiver. This propagation time $\Delta t_{reflection}$ and the uncertainty in the delay ε_{delay}, provides a search window for the reflected pulse. The start of the data buffer to be used to locate the reflected pulse should be

$$t'_{0reflection} = \Delta t_{reflection} - \varepsilon_{delay}$$

Where $t'_{0\,reflection}$ is the start of the search window.

The length of the search window is the sum of the pulse length, expanded by the maximum expected Doppler (which is small as all motion is current, or current induced only) and twice the delay uncertainty.

The direct and reflected signals were simulated for the closest point of approach in the trials geometry shown in Figure 8, with a water depth of 500 m. White noise of equal amplitude to the target return was added to the signal. There was no interference between target echo returns and boundary reflected signals.

The true value for the difference in integrated intensities for the received signals (in the absence of noise) was

$RL_{r,ref} - RL_{i,ref}$ = -30.9 dB.

The result using (2) and the received time series signals plus noise was

$RL_{r,t\_series} - RL_{i,t\_series}$ = -24.9 dB.

Using the correlation method, as described above

$RL_{r,corr} - RL_{i,corr}$ = -31.1 dB

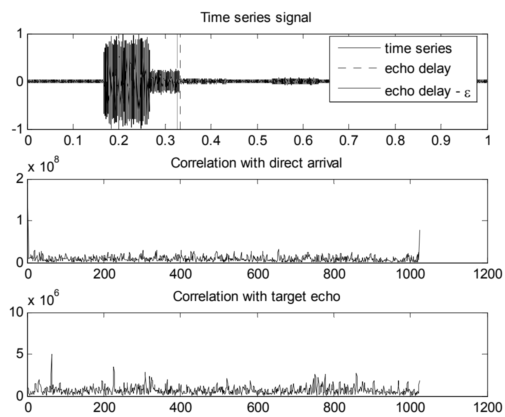

Figure 8 - Correlation of direct and reflected pulses

Figure 8 shows the original time series data, with markers for $\Delta t_{reflection}$ (dotted) and $t'_{0\,reflection}$ (dashed). The start of the buffer for the target return data was at $t'_{0\,reflection}$.

CONCLUSION

The automated measurement of submarine acoustic target strength in low SNR environments is theoretically possible by augmentation of existing noise ranging systems. The effectiveness of these target strength trials will be dependent on the planning of the trials geometry.

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