WIDEBAND UNDERWATER ACOUSTIC COMMUNICATION

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INTRODUCTION

The performance of any communication system is conveniently described by Shannons information theory [1], which defines the information capacity of the channel in terms of bandwidth, signal power and noise power. Conventionally, communications systems attempt to gain the maximum data rate for given system noise and channel bandwidth by using a variety of techniques to both reduce the required signal bandwidth for a given data rate, and equalise the bandwidth to the channel transfer function which is assumed to fit a stationary additive white Gaussian noise (AWGN) model.

An underwater acoustic communications channel is poorly modelled as an AWGN channel due to the combined effects of multipath, frequency selective fading and non uniform noise background. A technique widely employed in RF terrestrial communications, to mitigate against such effects, is to purposely increase the transmission bandwidth, beyond the data rate such that the bandwidth-time product (BT) available within a single message bit is increased and the system realises a performance improvement due to the processing gain achievable for bit correlation. Systems which employ this technique are generically termed spread spectrum systems.

The application of conventional spread spectrum techniques to underwater acoustic communications is constrained by two major factors; achievable transmission bandwidth and the effects of Doppler shift. Since the processing gain advantage of spread spectrum is dependent on correlation detector performance, increasing the signal BT product increases the susceptibility of the signal to Doppler.

A convenient method of spreading the transmitted signals spectrum is to use digitally generated pseudorandom binary sequences (PRBS) which are multiplied with the data modulated signal. Since the codes are unique and repeatable, a remote receiver is able to generate an exact local replica for correlation detection, subject to range and radial velocity uncertainty, which translate to time delay and Doppler shift in the received signal. Since the radial range and velocity are unknowns, the receiver must perform a range-Doppler search in order to synchronise its local processed PRBS to the received signal in both range and Doppler. Once synchronisation has been achieved the system must subsequently track the signal in range and Doppler.

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This paper presents experimental results obtained during deep ocean experiments, conducted to investigate the Doppler and transducer limitations of underwater acoustic spread spectrum performance. Results are presented for off-line analysis, which identifies detector performance and range-Doppler ambiguity at various points in a dynamic run geometry, for both positive and negative radial velocity. The results of real time analysis using a prototype spread spectrum receiver are presented which demonstrate the capability of a remote receiver to synchronise to a spread spectrum transmission initiated from a mobile transmitter and to subsequently track the transmitter in both range and radial velocity throughout regions of positive and negative Doppler shift identified later in the off line analysis.

TRANSMITTER

The generation of the data modulated signals was realised in software using a 66MHz 486 IBM PC compatible. The transmitter comprised two programmable PRBS generators, which could be programmed for given codes and filter characteristics. The resulting signals were then gated to form a modulated seamless wideband transmission. Since the signal is generated and processed in software, it is uniquely repeatable at the receiver assuming the receiver has knowledge of the spreading code characteristics and any subsequent processing.

RECEIVER

The receiver system comprised two Motorola DSP96002 boards operating synchronously. The boards were hosted by an IBM PC compatible, which provided a high level windows interface to the system. Each processor was programmed by the user to detect on a predefined spreading code and code characteristics. Once programmed and activated the systems await a synchronisation signal. This signal informs the processors to begin their range-Doppler search. In a practical system both transmit and receive would be synchronised to an absolute time reference in order to accurately determine

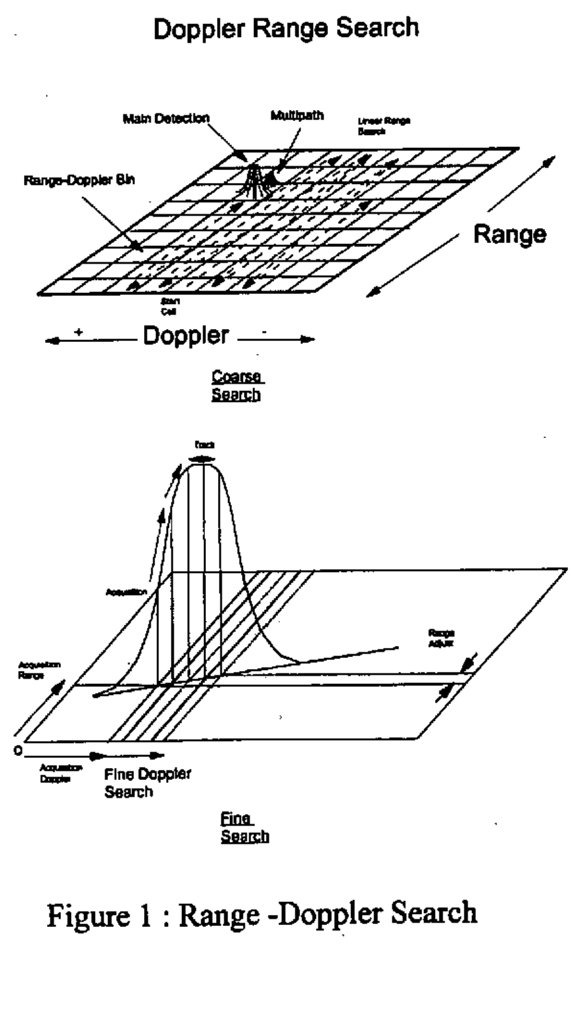

Figure 1 : Range -Doppler Search

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acquisition range. Once the initial search is started, each processor will attempt to detect its predetermined code which involves a range-Doppler search. The system defaults to a linear range search, stepping Doppler at the end of each range limit. For this search strategy the user controls the initial Doppler, the range of Doppler and the search step size. The range search is conducted at 3 km intervals out to a user defined search limit. Figure 1 illustrates the search process, with the system evaluating each range-Doppler bin until a detection is made. The bottom graph illustrates system operation during fine search, once an initial detection is made. Here the system attempts to localise the ambiguity peak by conducting successive correlations at small Doppler offsets and comparing the detector outputs for each correlation. In this way the system 'climbs' the ambiguity surface and is able to remain at the peak during the track phase. In a practical situation the location of this peak is constantly varying in range and Doppler. The range offset from initial acquisition may subsequently be used to correct the acquisition range. For the experimental results presented later, the receiver system was configured for single code operation.

SEARCH PHASE

The system block diagram for the initial search phase is illustrated in figure 2. Since the system operates in real time a double buffering technique is used, with signal sampling occurring as an event driven interrupt at the required sampling frequency. Once a valid half buffer acquisition has been obtained the resulting signal is processed for positive and negative Doppler, as dictated by the current Doppler search position. Since the detection is based on a digital matched filter (DMF), this operation has to be performed for original and delayed versions of the signal, so that the output of the DMF has uniform processing gain over the observation window. The Doppler processed signal is then equalised across the transmission bandwidth and correlated with the locally generated and filtered PRBS sequence. The resulting DMF outputs are overlap-save processed and then fed to the detection

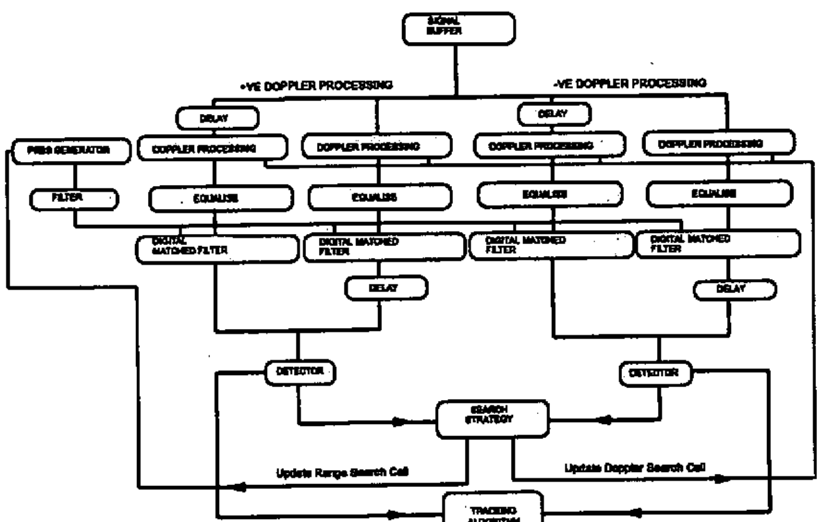

Figure 2 : Search Phase

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algorithm which identifies possible detections. If a detection exceeds the detection threshold, the system will commit to track and the track algorithm commences. Otherwise the system will re-evaluate the current search cell or move onto the next cell depending on the user programmed search strategy. This requires reprogramming of the Doppler processing and PRBS generator as shown in figure 2. The current system performs the search at 3km intervals such that range ambiguity is searched piecewise, for each Doppler cell.

TRACK PHASE

Once committed to track, the system must acquire the exact Doppler of the received signal. In order to reduce synchronisation time the Doppler search is performed at a user specified interval. This interval invariably depends on the bandwidth-time (BT) product of the transmitted signal which controls the signals Doppler performance. Therefore once the system begins tracking, it is necessary to conduct a fine Doppler search to localise the ambiguity surface maximum within any one range-Doppler cell. Since the initial detection is unlikely to correspond to the exact signal range-Doppler, the system must adjust the acquisition range once the fine Doppler search is complete, to allow for the range error occurring as a result of the imperfect Doppler match. Upon entering the track loop, the system adjusts it's PRBS generator to synchronise it with the incoming signal. A fine Doppler search is then conducted by computing matched filter outputs for the initial Doppler plus and minus a fine search offset. Figure 3 illustrates the track loop, which is very similar to the search loop. The main difference is the track strategy, which controls the PRBS generator and Doppler processing to enable the system to track the received signal. Once Doppler track has been achieved, the system computes acquisition range, corrected for the difference between the initial Doppler at acquisition and the fine Doppler track. The system will subsequently track the signal in Doppler and range, the latter computed by time integration of the velocity estimate from the Doppler track. The system maintains Doppler track by performing detection either side of the current Doppler track bin. The outputs are compared and the greater is chosen for the next Doppler update. In this way the system

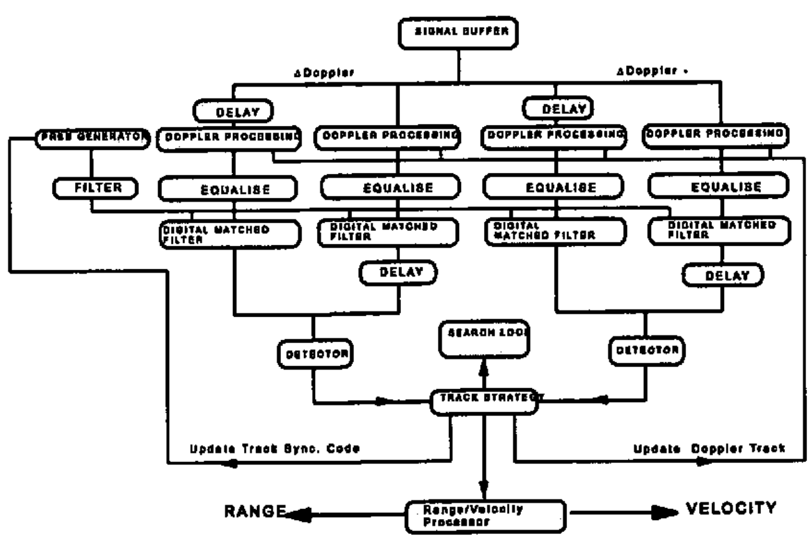

Figure 3: Track Phase

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localises the ambiguity peak (and hence the actual radial velocity) and tracks it. Once Doppler track has been achieved, the system can attempt to improve the detection in a number of ways. The most fundamental of which, is to increase the matched filter size. During the search phase the processing gain of the detector is limited by the signal Doppler such that larger filters actually reduce the achievable signal to noise ratio due to the contribution of uncorrelated code noise energy in the received signal. However once Doppler track has been accomplished, the system can extend the filter size, thereby increasing the processing gain since all of the signal energy remains correlated. However the finite Doppler resolution of the system provides an upper bound on filter size as will the increased processing overhead.

EXPERIMENTAL RESULTS

The results presented in this paper were obtained from data gathered during two mid Atlantic deep water sea trials using a baseband 1024Hz null bandwidth PRBS transmission. A realistic dynamic scenario was achieved by deploying sonobuoys from a moving transmitting trials ship which was equipped with a sonobuoy receiver. The results are presented in two parts. The initial set of results serve to highlight the problem of range-Doppler tracking, by illustrating the ambiguity surfaces obtained from off line analysis of sonobuoy data, recorded during a 7 knot turn around a sonobuoy. The second set of results illustrate the performance of the real time system using analogue trials data for a 40 minute run. The results illustrate input signal energy over a 2.048s integration period, the Doppler and range track, and the digital matched filter (DMF) detection to rms noise power ratio. These graphs illustrate the systems capability to both synchronise and track the transmitted signal, for continual variation in range and Doppler over a variety of ship manoeuvres and ship aspects

Since the data was recorded prior to the development of the real time system, no absolute time reference was recorded which meant that the system was forced to search over the entire code duration. For the results presented, the spreading code was based on a 16 element shift register giving a 65 second cycle time for a transmission bandwidth of 1024Hz which equated to a 96km range uncertainty during the search phase.

OFF LINE ANALYSIS

Figure 4 illustrates the range-Doppler ambiguity surfaces computed at six points in a run geometry labelled A-F. The run was conducted at 7 knots and involved a 180 degree turn around a sonobuoy. Surface A illustrates the range-Doppler ambiguity at a range of 2.1km. Here the detection is well defined and symmetrical in Doppler with a maximum at +7 knots. Surface B illustrates the range-Doppler ambiguity at a range of 1.2km. Here the detection is less clearly

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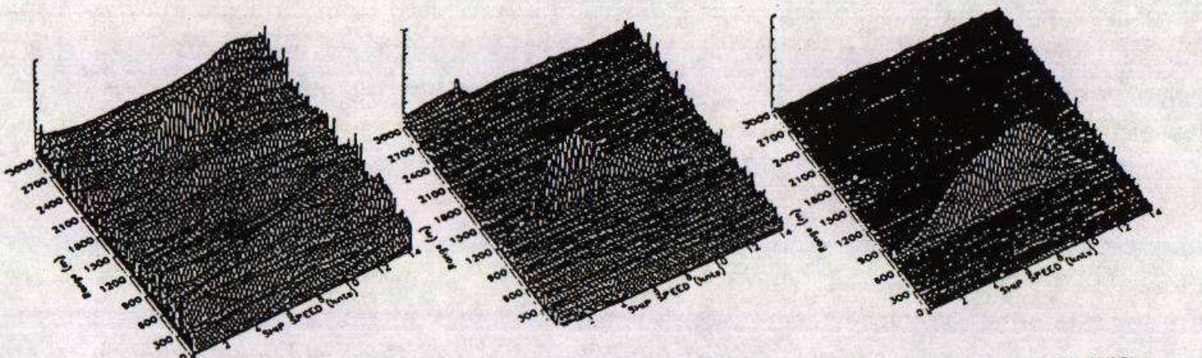
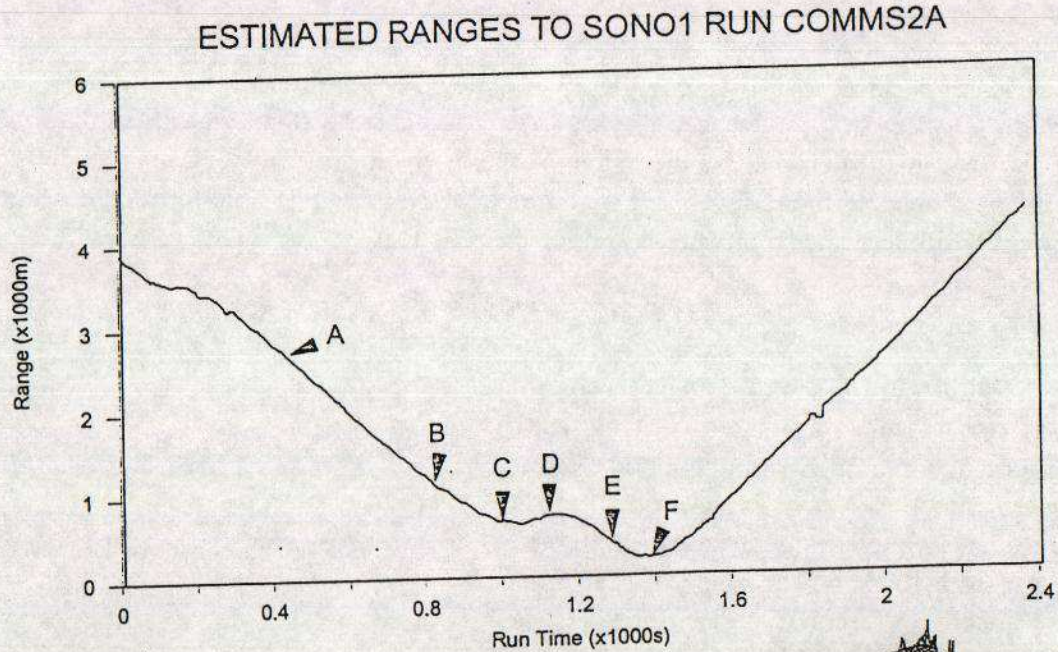
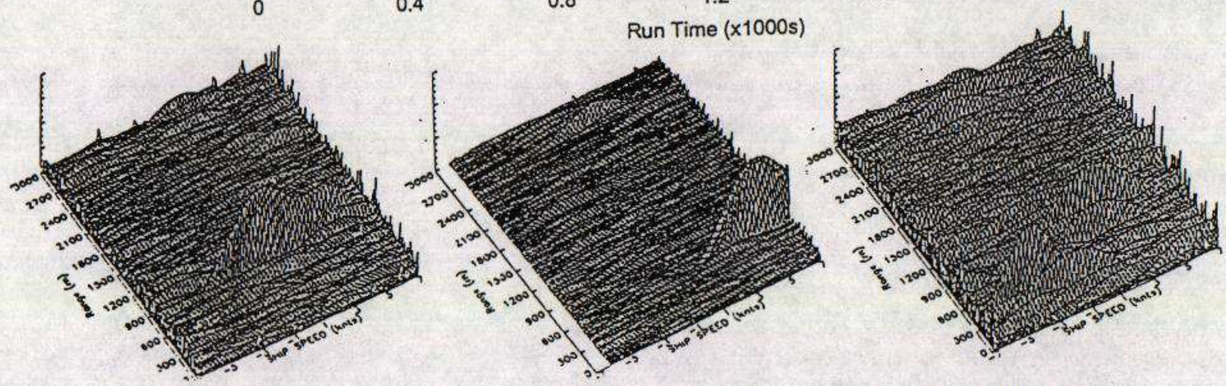


A : Ambiguity Surface T+450s B : Ambiguity Surface T+800s C : Ambiguity Surface T+1000s





D : Ambiguity Surface T+1150s E : Ambiguitv Surface T+1300 F : Ambiguity Surface T+1400

Figure 4 : Off Line Ambiguity Analysis

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defined in Doppler and a wider spread is evident, however the maximum detection remains at 7knots and a noticeable increase in signal to noise is evident. Surface C illustrates the detection at range 700m from the sonobuoy. The detection is clearly defined against the noise background, however the Doppler spread is significantly increased. Surface D illustrates the detection as the ship approaches a Doppler transition point. The detection is now centred on approximately 2 knots as the ship presents a broadside aspect. Due to the increase in ship noise the signal to noise ratio is noticeably reduced and reduces considerably as the ship presents a stern aspect. Surface E illustrates the detection as the ship completes the turn and approaches the sonobuoy on the return leg. Here the Doppler is centred on 6 knots, and the bow aspect ensures good signal to noise. Surface F illustrates the detection as the ship just passes the sonobuoy on the return leg. Here the Doppler has reduced to -2 knots, and the detection signal to noise is visibly reduced due to the increase in ship noise and the masking of the transmitted signal by the bubble layer from the stern aspect.

The series of surfaces A-F illustrate the low tolerance of the processed PRBS signal to Doppler. From the surfaces this can be seen to vary from 2-6knots at different points in the run geometry. This figure serves to emphasise the extent of the Doppler problem for spread spectrum acoustic communications and the requirement for a practical system to be able to track the signal in both range and Doppler. The results presented for the practical system illustrate exactly this.

PROTOTYPE SYSTEM PERFORMANCE

Figure 5 illustrates the run geometry used for the system results presented in figure 6. Analogue data recorded from sonobuoy 1 was replayed into the system which, once it had synchronised, logged signal energy, Doppler, range and DMF signal to noise in real time. The results presented are for system performance over a 300Hz band from 100Hz to 400Hz. Results were obtained for a variety of frequency bands across the transmission bandwidth of 1024Hz, which indicated system capability for bands off transducer resonance. Since no absolute time reference was recorded, the acquisition range was determined by computing the range difference between system synchronisation on the original transmitted signal and the sonobuoy signal. Bathythermograph recordings taken during both trials indicated a shallow

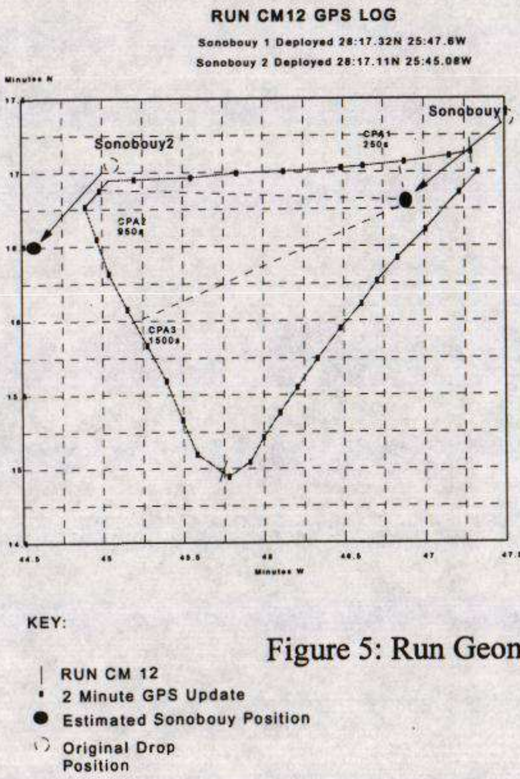

Figure 5: Run Geometry

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isothermal layer, with a thermocline beginning at approximately 70m depth which limited system range to approximately 3.5-4km

RANGE AND DOPPLER TRACK

Figure 6 illustrates the system outputs after synchronisation was achieved for the run geometry of figure 5. Initial acquisition was achieved at T+20s, at a range of 927m from sonobuoy 1. The ships radial velocity at synchronisation was +6 knots during the approach to sonobuoy 1. Shortly after synchronisation at T+200s, the Doppler reduces to -6 knots, with CPA occurring at T+250s. As the ship changes to stern aspect the system just manages to maintain the Doppler track despite a large increase in ship noise and wake disturbance, although appreciable variance in the detector output is evident due to the reduced signal level. At T+800s (range 2.2 km) the ship begins the 45 degree turn which the system tracks through the second Doppler transition point at T+950s, reaching a local maximum radial velocity of 2.5 knots at T+1100. The system maintains track as the ships radial velocity reduces, and the third Doppler transition point is reached at T+1500. The ships velocity then increases, reaching a value of -4 knots at the run completion.

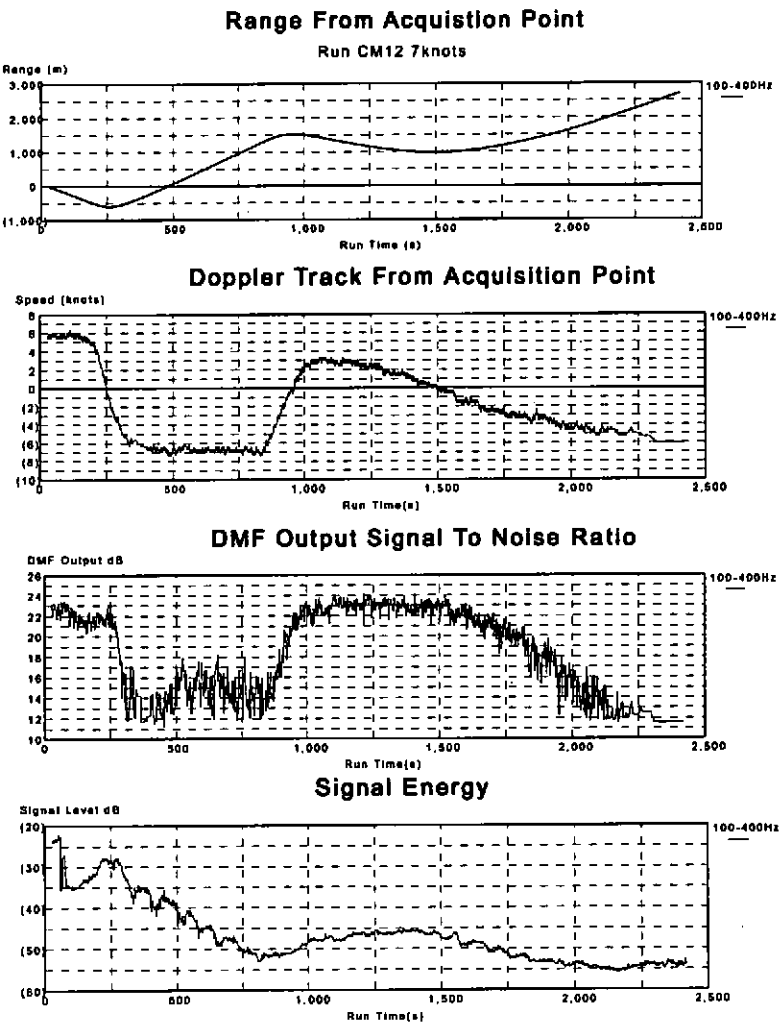

Figure 6 : Prototype System Performance During Track

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DMF SIGNAL TO NOISE PERFORMANCE

The DMF output illustrates the extent of signal degradation due to ship noise and the effect of bubble layer screening. Following initial synchronisation the DMF output falls slowly as the ship aspect alters from bow to broadside at the first CPA. After CPA a dramatic fall in the detector output is evident due to the stern aspect. At T+800s the turn commences and this is accompanied by a dramatic increase in detector output as the ship presents a broadside aspect to the sonobuoy during the second Doppler transition point. From T+1000s to T+1500s the detector output is seen to slowly increase as the ship approaches the third Doppler transition point at which point the ship slowly presents a stern aspect and the detector output is seen to fall less dramatically with loss of track occurring from T+2000s onwards. The signal energy plot illustrates the signal energy over a 2.048s second integration period. Noticeable from the plot are marked nulls in the signal energy, believed to be caused by a multipath interference effect dominated by ship noise in the 200-300Hz region as a result of the shallow isothermal layer. As the initial CPA is passed the signal level falls sharply by approximately 12dB . The level continues to fall reaching a minimum at T+800s of -50dB at which point the turn begins resulting in a slow increase in signal energy just prior to the second Doppler transition. The signal energy increases to a second maximum at T+1500s. From T+1500s onwards the signal energy reduces as the ship gradually presents a stern aspect.

TRIALS DATA OBSERVATIONS

The preceding results have illustrated a number of important features of the signals performance throughout the runs and the various factors contributing to the systems performance. The detection of coherent signal energy throughout the runs is made against a background of numerous noise sources which include ship noise, code noise contributions from multipaths, and ambient noise. Due to the dynamic nature of the experiments these noise sources vary in frequency and time such that the spectral distribution of the noise and its total energy vary throughout the run duration. Factors influencing the noise characteristics include range, ship aspect, ship speed, ship turns and channel propagation characteristics. Similarly the transmitted signal performance is also affected by ship aspect and propagation characteristics. The result is a complicated fluctuation in signal to noise ratio and the isolation of actual signal to noise performance for such a dynamic scenario is very difficult. However, a number of interesting observations can be made from the preceding results.

Despite transmission through a resonant transducer, reliable tracking was achieved for frequency bands off resonance. The performance of the system in these bands suggest the possible advantages of selective, weighted, incoherent integration of detector outputs, to improve detection by capitalising on favourable frequency bands in the transducer response.

The results have highlighted the systems performance through the bubble layer caused by the ships propeller. The system results indicate improved bow aspect detection falling slowly for broadside and sharply for stern aspects. This suggests a marked decrease in the coherent signal to noise ratio in the band of interest due to a combination of increased ship noise coupled with increased absorption of the transmitted signal due to wake disturbance. The ability of the system to track through stern aspects illustrates the tolerance of spread spectrum signals to high channel dispersion and noise.

Throughout all runs multipath components were clearly identified, despite limiting the transmission bandwidth to 300Hz, thereby reducing the range resolution to 5m. The effect of multipath on system performance is two fold. Since the transmission is continuous the main detection is made against background noise and the uncorrelated code noise due to multipath, which, if suitably processed, could be used to enhance the main detection.

CONCLUSIONS AND FURTHER WORK

The results presented in this paper have conclusively demonstrated the performance of a real time spread spectrum underwater acoustic communications system which is capable of synchronisation and tracking a broadband signal transmitted from a moving platform at speeds of 7knots and ranges up to 4km. The system has illustrated the ability to resolve to 0.3knots in Doppler, and future planned enhancements will reduce this to 0.1knots during the fine track phase.

Further development will be directed at the isolation and use of the multipath energy to enhance system performance during tracking. This will pave the way for development of adaptive equalisation algorithms after fine Doppler track is established and multipaths isolated, by using the signal knowledge to define the channel behaviour.

To conclude, it is clear that spread spectrum acoustic systems have a key role to play in underwater communications and position fixing applications by virtue of their tolerance to multipath, frequency selective channel fading and coloured noise.

REFERENCES

1 **Shannon C.E .,Communications in the Presence of Noise ,Proc IRE,Vol37,No 1, January 1959, pp10-21**