

## FM slide (chirp) signals: a technique for significantly improving the signal-to-noise performance in hydroacoustic assessment systems

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### Abstract

Nearly all acoustic systems used for fisheries and biological oceanographic studies have to date used systems that transmit short CW tone pulses. One of the characteristics of this type of system is that the user of the system is forced to trade-off spatial resolution with ability to minimize the adverse effects of noise. This paper describes the application of a different type of signal, the FM slide or chirp, for fisheries and oceanographic acoustic assessment. These systems have the characteristic that the signal parameters can be selected to provide both good spatial resolution and good noise immunity. The basic theory of FM slides as well as some of the factors that must be considered when implementing this signal type in actual systems are described. Laboratory measurements and field results are presented that show the potential advantage of the FM slide or chirp signals over the more conventional CW tone pulse. © 2000 Elsevier Science B.V. All rights reserved.

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### 1. Introduction

In situ target strength measurement techniques require accurate measurement of the amplitude of single fish echoes received on one or more acoustic transducers. The quality of single echo amplitude measurements is affected by the ability to resolve echoes from individual scatterers from those of multiple scatterers, and the echo amplitude relative to the noise level. It is often difficult to achieve both a good signal-to-noise ratio and good echo resolution using a conventional echo sounding system. In conventional systems, good resolution can only be achieved by

transmitting short acoustic pulses. The signal energy in a received echo is proportional to the signal pulse duration.

Consequently, the signal-to-noise ratio for short conventional acoustic pulses will be much poorer than that for longer pulses. On the other hand, the signal-to-noise ratio can be increased by transmitting a longer pulse, but this will reduce the spatial resolution and the ability to resolve single scatterer echoes.

The solution to this tradeoff between single echo resolution and signal-to-noise performance is to use a different type of signal than the conventional tone-burst pulse. The type of signal considered here is called an FM slide or chirp. The FM slide signal provides both good spatial resolution and good signal-to-noise performance.

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Near the end of World War II, radar system engineers developed FM slide or chirp signals to improve radar performance (Skolnik, 1962; Berkowitz, 1965). Navy active sonar systems have used the technique for the last 30 years. However, until recently, the complexity and cost of the electronics required to implement the technique precluded its use in any systems other than high-performance military systems. The advent of powerful, low-cost digital signal processors has changed this.

## 2. Background

The functional block diagram and the input and output signal waveforms for a conventional tone-burst pulse echo sounder is shown in Fig. 1. The spatial resolution,  $\Delta R$ , that can be achieved using this type of signal and echo sounder is

$$\Delta R = \frac{c\tau}{2}$$

where  $c$  is the velocity of sound in water and  $\tau$  is the output pulse duration. If scatterers are separated in range by less than  $\Delta R$ , their echoes will overlap and they cannot be resolved as individual scatterers. A typical pulse duration used in echo sounders is  $\tau=0.5$  ms. For this pulse duration, the spatial resolution is

$$\Delta R = \frac{1500(0.0005)}{2} = 0.375 \text{ m}$$

The conventional tone-burst pulse echo sounder has an output signal-to-noise power ratio of

$$\text{SNR} = \frac{A_{\text{rms}}^2}{\text{BW} \times N_0}$$

where  $A_{\text{rms}}$  is the root mean square amplitude of the signal into the filter, BW the bandpass filter bandwidth in Hz and  $N_0$  is the spectral density of the noise into the filter. The filter bandwidth, BW, corresponding to the  $-3$  dB spectral bandwidth for a tone-burst pulse of duration  $T$  is

$$\text{BW} = \frac{1}{T}$$

When a filter with this bandwidth is used, the input pulse width,  $T$ , equals the output pulse width,  $\tau$ . Therefore

$$\text{SNR} = \frac{A_{\text{rms}}^2 T}{N_0} = \frac{A_{\text{rms}}^2 \tau}{N_0}$$

Both the range resolution and the signal-to-noise ratio are proportional to  $\tau$ . The signal-to-noise ratio in a conventional echo sounder using tone-burst pulses can only be improved by increasing the signal level or the pulse duration. The signal amplitude is limited by the transmitter output power and the transducer peak power handling capabilities, therefore, the pulse duration must be increased to increase the signal-to-noise ratio. Increasing the pulse duration decreases the ability to resolve closely spaced scatterers. In setting up a conventional echo sounder system, one is forced to make a tradeoff between spatial resolution and signal-to-noise performance.

Fortunately, there is a way around the dilemma of signal-to-noise ratio versus spatial resolution encountered with tone-burst pulse echo sounders. The solution uses a different type of signal called an FM slide or chirp. The functional block diagram and the input and output signal waveforms for an FM slide based echo sounder is shown in Fig. 2.

The frequency of the tone-burst for the chirp signal is varied linearly within the pulse. The center fre-

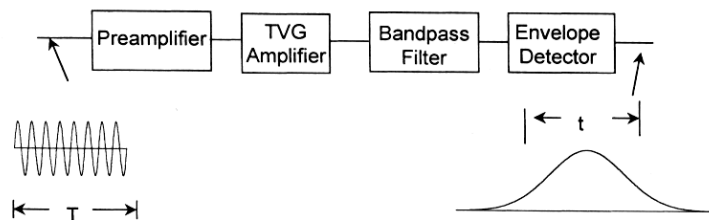


Fig. 1. Block diagram of conventional tone-burst pulse echo sounder receiver.

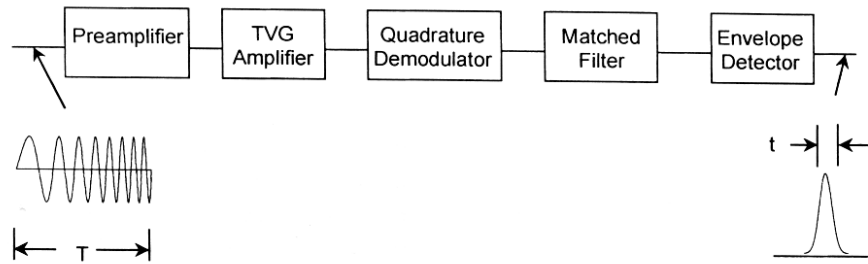


Fig. 2. Block diagram of FM slide echo sounder receiver.

quency of the chirp signal is usually selected to be at least 3–4 times the width of the frequency sweep. The received signal can be modeled as a narrow-band signal and the optimal receiver for this waveform consists of a quadrature demodulator which transforms the input signal into two low-frequency (or baseband) waveforms, and a special filter called the matched filter or pulse compressor. The matched filter delays the various frequencies in the chirp signal by different amounts such that the output is compressed in time and increased in amplitude. The pulse compression characteristics are diagrammed in Fig. 3. The width of the output pulse,  $\tau$ , is a function of the range of frequency, or bandwidth, of the input pulse:

$$\tau = \frac{1}{f_2 - f_1} = \frac{1}{\text{BW}}$$

where  $f_1$  and  $f_2$  are the minimum and maximum frequencies, respectively, in the chirp signal. The resolution for the chirp signal is a function of the output pulse width,  $\tau$ , and is not a function of the received pulse width,  $T$ :

$$\Delta R = \frac{c\tau}{2}$$

The signal-to-noise ratio at the output of the matched filter is the same as for a tone-burst pulse of width  $T$ :

$$\text{SNR} = \frac{A_{\text{rms}}^2 T}{N_0}$$

where  $A_{\text{rms}}$  is the root mean square amplitude and  $T$  is the duration of the FM slide signal at the input to the quadrature demodulator and matched filter. The input pulse duration,  $T$ , determines the signal-to-noise ratio and the output pulse duration,  $\tau$ , determines the resolution. Therefore, by properly choosing the input pulse

duration and frequency range of the chirp, it is possible to achieve both good spatial resolution and good signal-to-noise performance. The following example compares the performance of a conventional tone-burst pulse system and FM slide or chirp system. Both systems are set up to provide 0.15 m of range resolution and have the same transmit source level.

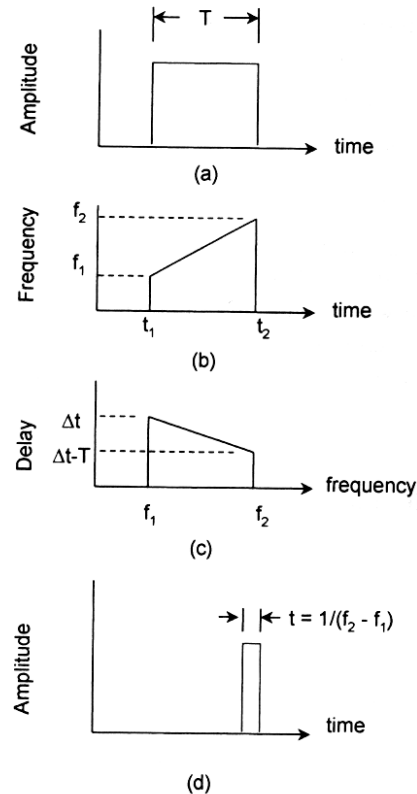


Fig. 3. Pulse compression characteristics: (a) input pulse echo envelope; (b) plot of chirp frequency vs. time; (c) matched filter time-delay characteristics; (d) output pulse envelope.

*Case 1.*

Tone-burst pulse with  $T = \tau = 0.2$  ms

$$\text{Spatial resolution} = \frac{c\tau}{2} = \frac{1500}{2}(2 \times 10^{-4}) = 0.15 \text{ m}$$

$$\text{Signal-to-noise ratio} = \frac{A_{\text{rms}}^2}{N_0} T = (2 \times 10^{-4}) \frac{A_{\text{rms}}^2}{N_0}$$

*Case 2.*

5 ms long FM slide with  $\text{BW} = (f_2 - f_1) = 5000$  Hz

$$\text{Spatial resolution} = \frac{c}{2\text{BW}} = \frac{1500}{2(5000)} = 0.15 \text{ m}$$

$$\text{Signal-to-noise ratio} = \frac{A_{\text{rms}}^2}{N_0} T = \frac{A_{\text{rms}}^2}{N_0} (5 \times 10^{-3})$$

Note that although both signals have the same spatial resolution, the FM slide has a signal-to-noise ratio that is 25 times as large as that for the conventional tone-burst signal. In general, the signal-to-noise ratio improvement,  $G$ , that can be achieved with an FM slide signal is

$$G = (f_2 - f_1)T = \text{BW} \times T$$

or in decibels,

$$G_{\text{dB}} = 10 \log_{10}(\text{BW}) + 10 \log_{10}(T)$$

For the example above, the FM slide will have  $G_{\text{dB}} = 14$  dB. Another way to look at this is that the FM slide will provide the same signal-to-noise ratio and the same spatial resolution with a transmit power that is  $\frac{1}{25}$  (14 dB less) that of a tone-burst pulse system.

### 3. Applications

The various factors that can affect the signal quality in acoustic assessment systems need to be briefly discussed to further explain the benefits of FM slide signals. Additive noise and/or reverberation can adversely affect acoustic systems. There are many sources of additive noise, including thermally generated noise from the random motion of molecules in the water and electrons in the electronics, breaking waves, flow noise for towed systems, shipping noise, etc. Reverberation is the unwanted received acoustic back-scattered signal from objects in the water, from the

surface, and from the bottom. Reverberation adversely affects the performance of acoustic systems and is usually considered a type of noise. However, the characteristics of reverberation are very different from that of additive noise. For example, if the echo sounder transmitter is turned off, the echo sounder output will not contain any of the effect of reverberation but will still contain noise. Reverberation cannot be removed by any processing operation such as filtering, and the reverberation effects are the same for both tone-burst and FM slide systems with the same output pulse width. In particular, the FM slide signal and the associated matched filtering does not remove the adverse effects of reverberation. Therefore, FM slide-based echo sounders will have the greatest benefit in cases where the system performance is primarily limited by additive noise. An example where this will be the case is an acoustic survey of small fish or plankton at relatively long ranges in a lake or ocean environment. In this case, reverberation will be minimal and performance will be primarily limited by additive noise.

An example of an application where reverberation is the primary factor limiting system performance is an acoustic system designed to detect fish at short range in a shallow river that contains a lot of entrained air. In this case scattering from the surface and bottom of the river as well as from the air bubbles in the river will be the major contributors to the degraded output signal quality.

The primary acoustic assessment application where both good spatial resolution and good signal-to-noise performance is required is for single scatterer (fish or plankton) echo counting and single scatterer target strength measurement. In both these cases, good spatial resolution is required to isolate single scatterer echoes from echoes made up of returns from two or more scatterers. Furthermore, the noise-induced bias and variance of the target strength estimates are reduced as a result of the higher signal-to-noise ratio.

The processing used for FM slide signals preserves superposition of the backscattered energy from the acoustic scatterers. In other words, the total energy in the processed FM slide output signal is proportional to the average energy per scatterer times the number of scatterers. The echo integration acoustic assessment technique can therefore be used with FM slide signals as well as with CW tone signals. Noise can adversely

affect the quality of echo integration abundance estimates. For a given received noise spectral density level, the signal-to-noise ratio at the output of an echo integrator output is proportional to the energy in the transmit pulse. This is true for both FM slide and CW pulse tone signal. The advantage that the FM slide provides over the CW tone is that it is possible to have a much narrower integration depth strata with the FM slide. As a particular example, consider the use of a 5 ms CW tone signal and a 5 ms, 10 kHz bandwidth FM slide signal. The effect of the additive noise on integration processing of these signals is the same. However, the returning echo from a 5 ms CW tone signal is the composite return from all the scatterers in a 3.75 m range interval, while the returning echo from a 5 ms, 10 kHz bandwidth, FM slide signal is only dependent on the scatterers in a 0.075 m interval. Integration depth strata as small as 0.1 m could be used for the FM slide, while the smallest useful depth strata for the CW tone signal would be about 4.0 m.

#### 4. FM slide implementation

Commercial split-beam echo sounder systems have been developed to implement either the conventional tone-burst pulse or FM slide signal types. One particular system developed by HTI uses multiple digital signal processor chips to implement all the processing function normally achieved using discrete components. The HTI system has selectable pulse widths up to 5 ms in duration with FM slide bandwidth up to 10 kHz. The result is a system that can have the same resolution as a 0.1 ms tone-burst pulse based system with an output signal-to-noise ratio that is a factor of 50 (17 dB) higher.

There are various issues that should be considered in implementing a FM slide echo sounding system. The bandwidth of the transducer should have a flat frequency response over the bandwidth of the slide signal. This can be achieved by proper transducer tuning without a significant loss of transducer efficiency for bandwidth of 10 kHz or less at typical acoustic operating frequencies (>30 kHz). Another issue that can arise with FM slide systems is that large targets can produce smaller false targets that are shifted in range. These false targets are caused by range lobes in the response of the matched filter. A

technique called frequency domain windowing was developed by radar designers to eliminate the range lobes and the associated false targets (Skolnik, 1990). The matched filter implementation in HTI systems uses this same approach to remove range lobes.

Acoustic properties of the propagation media and the scatterers could also affect the performance of FM slide systems. If there is significant structure in the frequency response of the scatterer within the bandwidth of the FM slide, there will be some reduction in the processing gain achieved by the matched filter. For typical acoustic operating frequencies, the frequency response of the scatterers are approximately flat over a bandwidth of 10 kHz. The target motion in the direction of acoustic propagation can induce phase variability in the return echo (the Doppler effect). The effect of target motion on the signal and the resulting reduction in processing gain has been analyzed for the signal parameters used for the HTI system. Target velocities of 1 and 5 m/s in the direction of propagation will reduce the processing gain for a 200 kHz, 5 ms pulse duration, 10 kHz slide bandwidth system by 0.03 and 0.35 dB, respectively. In nearly all cases of interest, the targets are illuminated from either the top or side aspect and the target velocity will be much less than 1 m/s. It can therefore be concluded that loss in processing gain due to target motion is not an issue. The characteristics of the propagation media can also change over time. If the propagation media changes significantly over the duration of the signal pulse, there will be a loss in the matched filter processing gain. However, acoustic propagation experiments have shown that the coherence time of the propagation media is much greater than the 5 ms pulse duration. The effects of propagation media variations can therefore be ignored.

The performance advantages achieved with the FM slide waveform are illustrated in Fig. 4. These data were collected using an HTI Model 240 digital split-beam echo sounder. These figures show the unprocessed input waveform with noise and the detected output waveforms for a 0.2 ms CW tone and a 10 kHz, 5 ms FM slide waveform. The detected pulse width output is similar for both signals. The data shown in the four figures illustrate the effect of a 30 dB range of input signal-to-noise ratios. In the high signal-to-noise ratio case shown in Fig. 4a, both the tone-burst and FM slide detected outputs are well above the output noise.

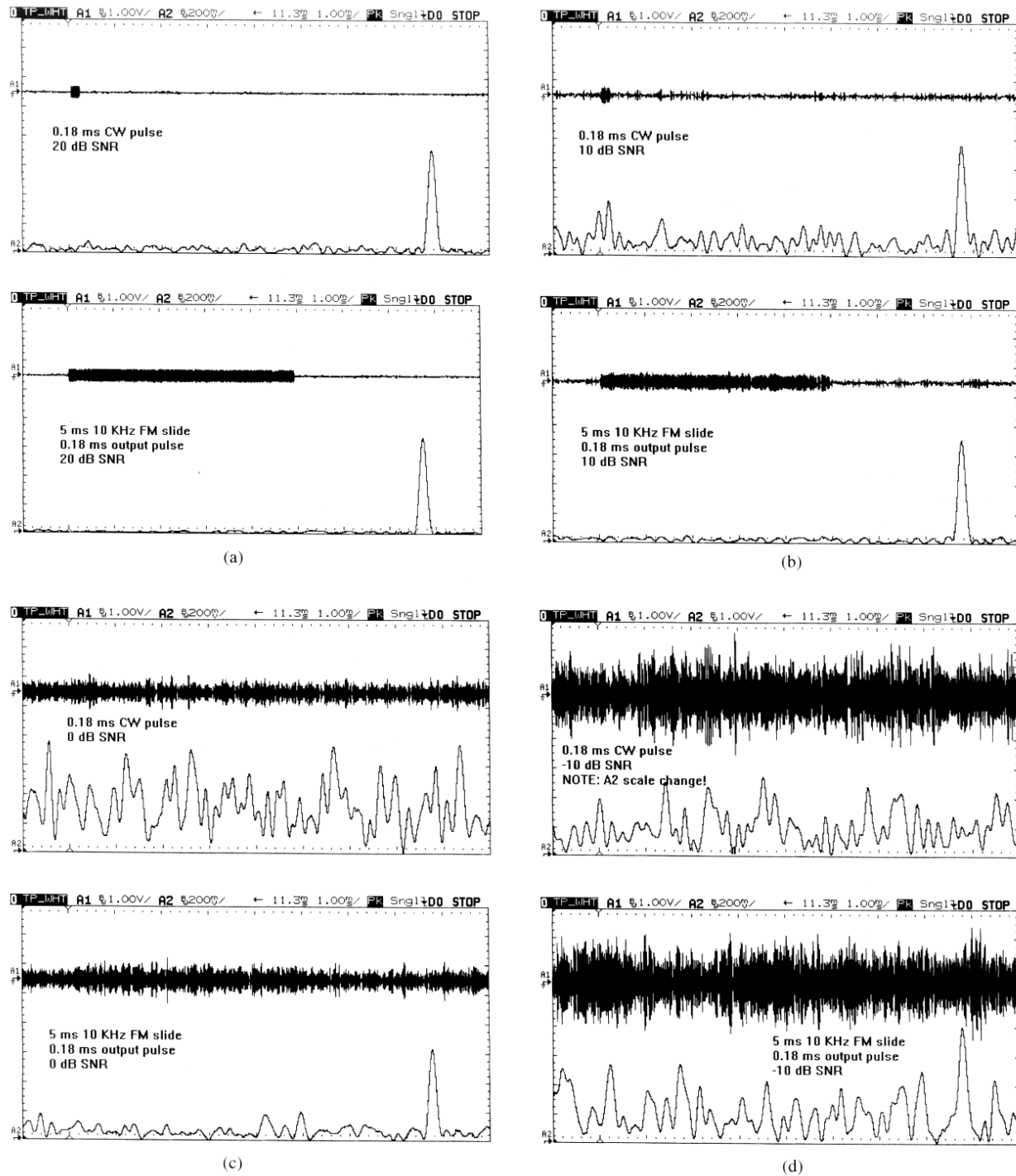


Fig. 4. Oscilloscope displays showing tone-burst pulse and FM slide echo sounder outputs. The upper and lower scope displays show the input and output waveform for the tone-burst pulse and FM slide, respectively. The input signal-to-noise ratios for Fig. 4a–d are: 20, 10, 0 and –10 dB.

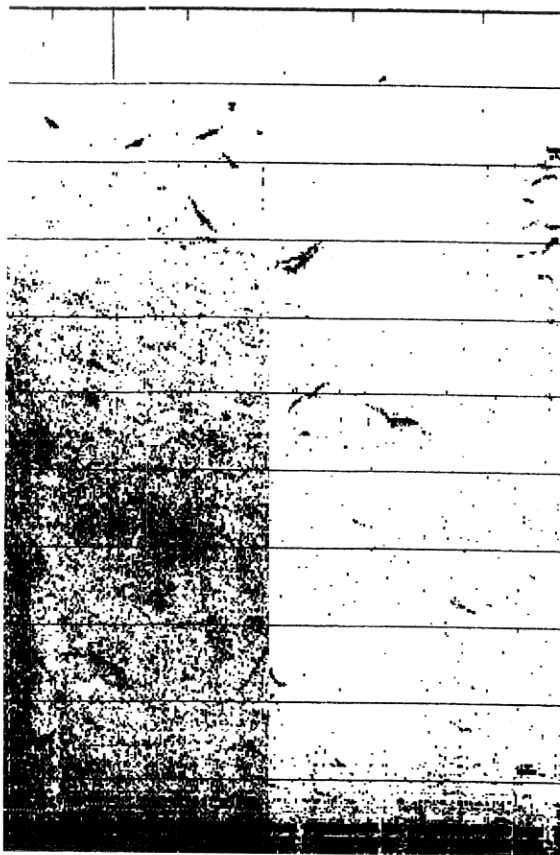


Fig. 5. Echogram showing the relative noise performance of two signal types. The left-hand side of the echogram is for a tone-burst signal and the right-hand side is for an FM slide. Both signals have the same transmit power and spatial resolution.

However, as the noise is increased, the tone-burst pulse detected output is increasingly dominated by the noise. In fact, for the signal-to-noise ratios shown in Fig. 4c and d, it is impossible to determine which tone-burst output peaks are due to the signal and which are due to the noise. On the other hand, the output signal-to-noise ratio for the FM slide is sufficient to accurately locate and measure the amplitude of the signal for all signal-to-noise ratios shown.

The advantage of the FM slide signal is also illustrated by comparing an echogram collected with both the FM slide and tone-burst pulse signals. Fig. 5 shows an echogram collected with the HTI Model 240 system initially using the tone-burst pulse and then switching to the FM slide. Note that noise dominates the echogram output at longer ranges for the tone-burst pulse signal. The FM slide signal suppresses the noise and provides a clean echo traces over the entire depth range.

## 5. Conclusions

Acoustic systems designed to make fish or plankton target strength measurement at medium and long ranges are often limited by the achievable output signal-to-noise ratio. Prior to the use of FM slide signals, the only ways to increase the signal-to-noise ratio were to increase the transmit power or increase the duration of the transmitted acoustic pulse. The 17 dB performance improvement described in this paper is equivalent to a factor of 50 increase in transmit power or a factor of up to 2.66 increase in range for the same transmit power with a tone-burst pulse signal. This technique can be applied to single beam or multibeam (dual or split beam) acoustic systems and can be used with echo counting, echo integration or target strength measurement processing. The small increase in the complexity and cost of acoustic systems, which implement this technique, is more than justified by the significant performance improvements achieved.

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