Recovering Data and Voice Recorders Following At-Sea Crashes

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Abstract – **The international aviation safety community has concluded that existing methods of blackbox localization and recovery are not effective in deep ocean situations, and occasionally not effective even in relatively shallow water when the acoustic pinger is buried or covered in debris. The majority of these pingers are provided by two companies, Teledyne Benthos and Dukane, according to pre-determined form and function, and these devices are essentially "built to spec." The purpose of this paper is to identify the shortcomings in the existing, decades-old functionality and to recommend the introduction of acoustic modem technology to provide orders of magnitude improvement in blackbox localization and data recovery.**

Fundamental ocean physics clearly indicates that the following conceptual changes should be considered:

1. **The current pinger technology operates at nearly 40 kHz frequency. Simply reducing the frequency to perhaps 12 kHz will substantially increase range in seawater and even improve performance when the device is covered in sand or debris.**
2. **The devices use very short sinusoidal tones (usually called tonals) as their signals. Ocean propagation often is highly selective in frequency due to the constructive and destructive alignment of propagation paths – some frequencies are supported, others are canceled. Furthermore, it is difficult to transmit sufficient energy into the water with these signals. Tonals are very poor candidates for robust, reliable ocean signaling.**

In addition to fundamental issues, the current system operates by a water-activated commencement of repetitive transmissions (pings) of these short tonals the moment the device enters the water – even though no listening devices are present. This is a waste of energy.

In this paper, we provide a brief overview of acoustic propagation from the perspective of its differences with more commonly understood radio frequency (RF) propagation. We follow that with our suggestions for substantial changes in operational concept, specifically arguing for wider bandwidth waveforms with more sophisticated receiver processing. However, given the effort to utilize more complex systems, we recommend they be further adapted to support underwater acoustic communications (acomms). This will provide blackbox and crash recovery far more effectively than is now possible, and can support data recovery when the devices themselves cannot be recovered. In particular, acomms modems can be used in support of long-range, accurate position estimation by either manned or unmanned platforms. Our proposed system will be somewhat larger than the present system, but it will significantly enhance the ability to find a submerged black box.

I. INTRODUCTION

Figure 1 shows an overview of the fundamental problem addressed in this paper. We show a submerged aircraft with a conventional recorder which may have been dislodged during the crash. Attached to the recorder (unless it has also been dislodged) is a small, cylindrical tube which functions as an acoustic beacon, as shown imposed in the upper-right corner of the figure. This beacon emits acoustic energy as extremely short continuous wave, or "CW" sound waves which exist within the range of 36.5 to 38.5 kHz. For historical reasons, the beacon is referred to as a pinger, and the sound waves as pings.

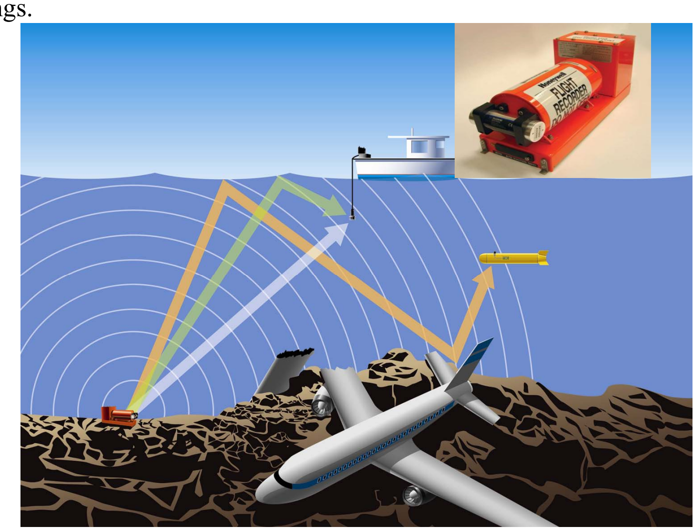

Figure 1. A sketch of a submerged airplane with a dislodged pinger. Colored arrows indicate possible directions that the pings might follow to either of two receivers.

The problem we address is indicated by the arrows in the figure: sound does not necessarily follow a single, direct path from source to receiver. Not only do these preferred paths overlap in time (hence causing mutual interference), they also impose different amounts of loss in the delivered energy. We refer to this situation as "multi-path" and it can be extremely deleterious with CW waveforms.

The path losses caused by attenuation (as opposed to geometric spreading) are highly dependent on the frequency of

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the waveform. In the present 39 kHz case, the ping will lose approximately 75% of its energy when traveling a kilometer. This severely constrains the range at which a detection system can expect to discover the blackbox.

High frequency, CW pingers are a decades-old legacy technology designed for an earlier age. They do not reflect the benefit of modern electronics, our newer understanding of ocean physics, or implementable mathematical approaches to exploiting sound propagation in the sea. This paper suggests a progression of alternatives which do reflect modern approaches to subsea acoustic activities.

II. CURRENT PINGER TECHNOLOGY

In this section we provide an overview of the likely performance of the current high frequency CW pinger-based recovery system. It is important to note that the problems we describe involve both the pinger itself and the tools used to locate the pinger. Neither operates in isolation.

The most effective method for detecting a known waveform is to build a filter especially crafted to mimic the structure of the waveform as it will exist at the receiver (not necessarily as it existed when transmitted). Unfortunately, it is often impossible to know *a priori* what the ocean channel will do to a waveform, so instead we construct a compromise filter which reflects both its origination and the gross effects of the channel. For a CW ping, this is most appropriately a bandpass filter.

The existing design of blackbox pingers reflects an inability to (cost effectively) tune electronics to produce a pure CW at a precise frequency. Thus, the design calls for an approximately 10 ms CW ping to be transmitted anywhere within roughly a 2 kHz band (e.g., between 38 and 40 kHz). Unfortunately, this requires a receiver to use a detector operating with a 2 kHz wide bandpass filter. As the actual effective bandwidth of a 10 ms CW ping is only approximately 100 Hz wide, we see that the design imposes a severe mismatch – reflected in a 13 loss in signal-to-noise ratio (SNR) which is self-imposed by this poor design.

II A. Mutual Interference From Multipath

Waveforms traveling over different paths typically arrive at a particular point in space with differences in both arrival time and possibly phase shifts as well (for a CW waveform the two are generally indistinguishable). Such overlap can either enhance or degrade the resulting waveform, as described next. Figure 2 shows two figures side-by-side, each with two plots. The upper plot shows the time history of the ping (plus noise), while the lower plot shows the output of a (spectrally wide) bandpass filter. In both figures the same CW signal arrives over just two paths, but with very subtle differences in arrival time shown between the left and right arrivals. The SNR in both cases is quite high.

The conclusions to be drawn with current pinger design is that a high frequency CW waveform will suffer from excessive attenuation, may suffer from multipath interference, and will likely be lost in noise because of the wide filter.

Finally, the current receiver design provides for, at best, limited ability to measure the bearing from the receiver to the pinger, and NO ability to estimate range.

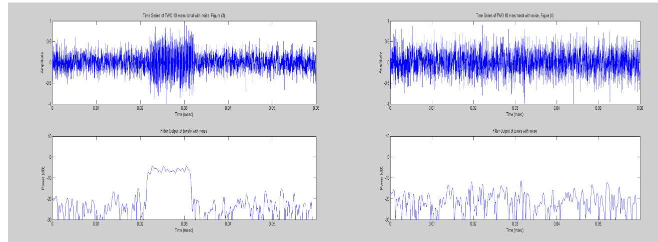

Figure 2. Two examples of a CW signal in noise arriving over two paths. On the left, the signal is apparent, on the right, with subtly different arrival times, it disappears.

III. BROADBAND SIGNALING

Signals occupying a bandwidth considerably wider than the inverse of their duration (a measure of a "CW" waveform) are considered to be broadband, and offer considerable advantage over the older technology. First, they are far less likely to disappear with multipath (see Figure 2), and second, we have the ability to craft different types of filters which can better extract the desired signal from the noise. Figure 4 shows two conditions similar to those of Figure 2. We show a so-called linear frequency modulated (LFM) waveform arriving over the same two paths used with the CW pings. The lower plots show the output of the special filter used with these LFM waveforms. The sharp peak identifies the arrival time of the signal, and its height relative to noise is a measure of output SNR, which is nearly the same in both conditions.

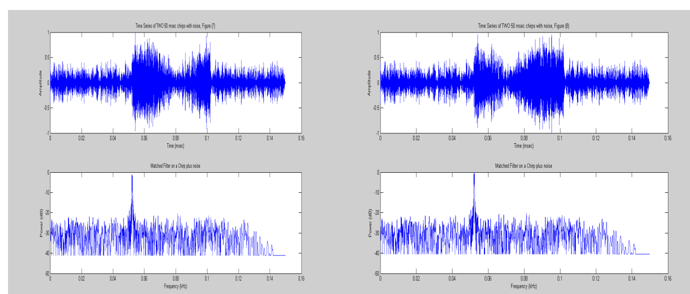

Figure 3. Two examples of an LFM signal in noise arriving over two paths with subtly different arrival times. In both cases, the signal is equally detectable.

It is important to note that the transmitter electronics must be more capable than with the current pinger design, and the receiver must (generally) be built around a micro-computer, such as a digital signal processor (DSP). However, even when operated at approximately the same center frequency, and transmitted with the same power, the signal should be detectable at several kilometers, rather than (at best) the one kilometer of the present system. Equally important, the use of signals such as the LFM permit the transmission of considerably more energy than a simple CW transmitter can provide (via longer, but lower power transmission).

The discussion at this point could still support the use of a beacon concept, as is done with the current pinger. That is, we could simply trigger the electronics to begin transmitting the broadband signal on a regular basis the moment the device enters the water. While this would improve performance, we can still do much better.

III A. Triggered Transmissions (Transpond Mode)

Unless the transmitter and the receiver have highly synchronized (and expensive) clocks, a beacon mode provides no information about range. Therefore, even if a signal is detected, it is – just out there in space somewhere. A far better solution is to restrain the blackbox system from transmitting unless it receives an interrogation from the search system. On the (reasonable) assumption that the now transmit/receive complex at the crash site has a well-defined time delay during which an interrogation is received and processed, and the reply is formulated and transmitted, we can estimate range. Simply put, we measure the total round trip travel time, subtract the known processing time, and divide by two to obtain an estimate of 1-way travel time. If we assume a speed of sound, we then have an estimate of the range. It is then an easy matter to continue interrogation while reducing the range – until the subsea unit is found.

At this point we have introduced a considerable increase in the complexity of the "pinger" attached to the blackbox. We have also added somewhat, although not significantly, to the receiver functions already required for broadband reception. However, by providing increased gain against noise (broadband) and range (transpond mode), we have accomplished two important things:

1. Battery consumption is reduced because the subsea unit only transmits on demand
2. The utility of the search unit is significantly enhanced.

III B. Reduced Frequency

The near-40 kHz operating frequency of the current pinger/beacon was likely selected because it admits of physically small and somewhat "sloppy" electronics. However, as mentioned, attenuation at such frequencies is severe. Were we simply to reduce the frequency to 10 kHz, we would lose perhaps 10% of energy rather than the present 75% – per kilometer This change alone would greatly increase the detection range. Perhaps equally important, such frequencies can be expected to escape from debris and sediment coverage much more than a 40 kHz signal would do.

The principal drawback to reduced operating frequencies is the corresponding increase in the physical size of the transducer. Whereas the present pinger has a button transducer that is perhaps less than 2 cm in diameter, the transducer required for 10 kHz will have a diameter on the order of 10 cm, and it will be much heavier.

III C. Spatial Directivity

The directivity of the pinger, meaning the directions in space into which it funnels energy, is a measure of considerable importance. One would desire equal radiation at all angles – spherical radiation. On a 2-dimensional plot, we would therefore expect to see a good approximation to a circle as a so-called beampattern. As an example, we show in Figure 4 a directional beampattern for a typical blackbox pinger, which is rather removed from a circular pattern (the levels are in decibels, or dB: a factor of 10 dB represents a change of 10 in terms of power). We should emphasize that the pattern obtained with the pinger actually attached to the blackbox (see Figure 1) is likely less desirable. We note that, at considerably lower frequencies (e.g., 10 kHz), it is a demanding endeavor to obtain reasonably "omni-directional" beampatterns for a broadband transmission. This must be a consideration when developing a replacement system for the recovery.

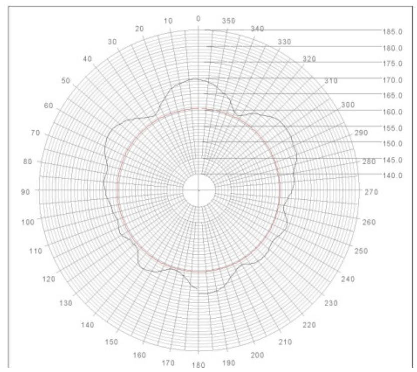

Figure 4. Beampattern for a typical blackbox pinger (not attached to the box structure).

IV. ACOUSTIC COMMUNICATIONS

On the assumption that we have moved away from simple CW tonal beacons to the complexity of 2-way broadband signaling, we can advance another significant step toward a major improvement in blackbox localization and data recovery by using underwater acoustic communications (acomms). The ability to query a remote system for status, including range, battery life, depth, etc., is inherently available with an acomms modem. Furthermore, the ability of a modem to individually address remote modems enables the search team to query any number of blackbox systems, without sustaining mutual interference.

An acomms message typically is a rather complicated collection of a variety of waveforms, as shown by example in Figure 5. An important feature of such a waveform is that there rarely, if ever, is a "false alarm." That is, if a signal is received, the demodulation and decoding is such that the composit waveform cannot be mistaken for anything else.

The obvious use of this acomms capability is to transfer information between or among modems. For example, should the blackbox system be equipped with a depth sensor (a low cost and inexpensive item not currently placed on the box), the search system can query the modem to extract the depth reading. Furthermore, the status of the recording mechanism and integrity of the data might be ascertained. Certainly "snippets" of the recorded data can be retrieved acoustically, although transferring megabytes of data this way is impractical.

A less obvious way to use the modem infrastructure is to add certain electronic assets to the search system (not the blackbox system) which enable it to ascertain the bearing of the remote modem. Bearing accuracy of less than 2 degrees is readily obtainable.

In summary, by enhancing the broadband system to incorporate acomms, we obtain the following benefits:

1. Precision localization in bearing and range, with depth available from an attached depth sensor.
2. Range of detection and immediate localization in deep water should exceed 10 km.
3. Extraction of snippets of stored data prior to physical recovery.
4. The crash site components remain in a low-power sleep mode until commanded by the search system to awaken.

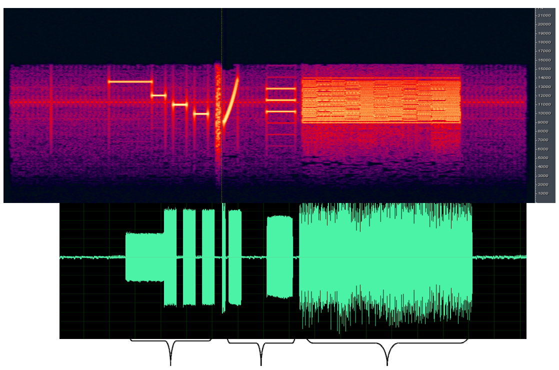

Figure 5. A typical (Teledyne Benthos) Telesonar communications packet

V. CONCLUSIONS

The principle drawback to the present CW pinger system is the enormous burden it places on a recovery system. The limitations of the pinger, as seen from an overall recovery system viewpoint, are the following:

- Limited range (< 1 km)
- No inherent ranging capability
- Poor quality control on transmit frequency
- Pings are severely impacted by ocean conditions
- Ambient noise/interference
- Multipath

While bearing estimation is possible with CW pings, the available methods require high SNR. The current receiver design inherently uses a far-too-wide bandpass filter to compensate for uncertain transmit frequency, which seriously reduces the available SNR. Furthermore, multipath conditions can further reduce SNR, again making bearing estimation difficult. Neither of these issues are as problematic with well-designed broadband systems.

Given that the present pinger is only detectable to about a kilometer, a crash in a 6 km deep ocean would require the receiver to be positioned at a minimum depth of 5 km, and that would only be effective directly overhead. Operating at such depths requires enormous resources – typically a large ROV with an accompanying large support vehicle.

By rebalancing the resources to put a more capable infrastructure with the blackbox, the search infrastructure can be substantially reduced. For example, a typical broadband acomms modem, operating perhaps at 10 kHz, would likely provide a useable detection range of 10 km, and it could be configured to provide immediate localization of the subsea unit upon first acquisition. Such an acquisition system can easily be carried by even a modestly-sized unmanned underwater vehicle (UUV) which can operate autonomously without the risk and expense of a towed ROV operation.