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Technical White Paper

Understanding the Performance of VEMCO 69 kHz Single Frequency Acoustic Telemetry

Document #: XDOC-004372 Version 05
February 19, 2008

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1. Introduction

1.1 Scope and Purpose of this Paper

The introduction of the VR2 monitoring receiver in 2000 and companion coded transmitters has spurred rapid growth in the use of acoustic telemetry to assess movement patterns, behaviour and site fidelity of fishes and invertebrates.

Three factors have been key to the success of this technology:

1. Low cost, easily deployable receiving capability
2. Our strategy to ensure that any receiver in the world can detect any transmitter
3. Transmitter coding schemes providing unique worldwide ID codes

VR2 69 kHz Receiver

These have enabled large continental (e.g. POST) and worldwide (e.g. The Ocean Tracking Network) initiatives as well as stimulating collaborative efforts between different research groups (e.g. The Central Valley Fish Tracking Consortium).

The objective of this paper is to provide an overview of the technology and how it can be applied. More detail related to guidance for the design of successful studies, performance limits, methods of handling and sharing data, etc. will be provided in Application Notes to be released from time to time.

1.2 VR2/VR3 Receiver Products

The VEMCO VR2 Monitoring Receiver introduced in 2000 is a submersible, single channel receiver capable of identifying VEMCO coded transmitters. It records the identification number, sensor data (if any) and time stamp from acoustic transmitters as the animal being studied travels within receiver range. Data is downloaded quickly and easily in the field, without opening the case.

Subsequent enhancements include:

- Increased Data Storage: from 2 to 8 Mbytes
- Bluetooth Wireless Interface to provide faster download and simultaneous download from multiple receivers
- Field Upgradable Firmware which, among other things, allows new transmitter coding schemes to be introduced without causing receiver obsolescence
- The VR3 and VR4 Families which facilitate the recovery of data from the unit by providing a remote communication capability by means such as satellite and underwater modem

None of these features impacts the receivers' core function; the detection of coded transmitters and storage of IDs and sensor data and, therefore, the concepts presented in this paper apply to all VR2s, VR3s and VR4s.

VR2 Deployed

VR3-UWM

1.3 Transmitter Coding Methods

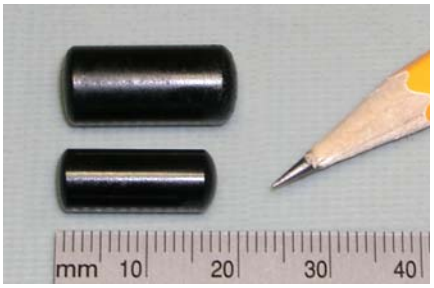
Acoustic Telemetry Coding Methods can be classified as shown in Table 1-1. The role of each method as well as shortcomings are also summarized.

Method	Coding Technique	Role	Shortcomings
Pulse Repetition Rate	Information is coded in the Repetition Rate of single frequency transmitted pulses.	Largely obsolete except for short term active tracking.	• Can handle at most a few tags simultaneously • Can "pollute" Receiving Arrays designed to detect other types of tags
Pulse Interval Coded	Binary Data is coded into the intervals between a burst of pulses. Typically the burst is followed by a period of silence.	Good general purpose approach -- optimal from the point of view of power utilization – which: • Can support large numbers of codes, significant number of simultaneous transmitters, etc. • Is compatible with easily deployed autonomous receivers	• Length of time to detect all Fish around a receiver increases as number of fish present increases • Low update rate from sensors
Spread Spectrum	We apply this terminology – not strictly correct in all cases – to any scheme which uses more than a single frequency or other form of modulation to increase data rate	Wide range of capabilities depending on complexity but at high end: • Capable of detecting multiple fish quickly • Significantly higher data rate potential than Pulse Interval Coding • Ability to more precisely estimate time of arrival giving better precision in triangulation systems	At high end: • Receiving technology is complex and therefore a challenge to implement in low cost, long life autonomous units • Transmitter electronics complexity and power requirements makes size/life tradeoffs less attractive than other methods

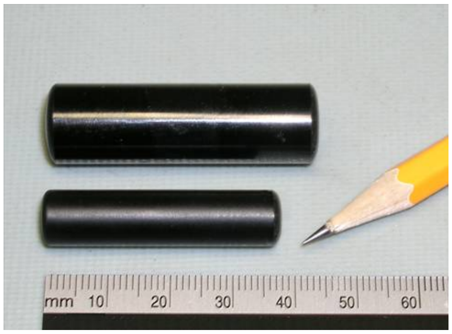
Table 1-1: Classification, Roles and Shortcomings of Acoustic Telemetry Coding Methods

1.4 VEMCO 69 kHz Pulse Interval Coding Telemetry "Network"

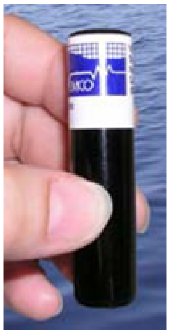
As can be seen from the above, Pulse Interval Coding forms a strong basis for general purpose telemetry applications and VEMCO 69 kHz telemetry products are based on this. These products include the V7, V9, V13 and V16 transmitter families offering multiple tradeoffs of range, size and life (including multiyear) and the VR2/VR3/VR4 receivers described in Section 1.1. The following photos are representative of 69 kHz Transmitters from the smallest to the largest.



V7 and V9



V9PT and V13PT (Pressure/Temperature)



V16 High Power Long Life

Key system features include:

- Large number of ID codes – 68k now potential to move to 192k and beyond as required
- Coding supports inclusion of sensor data and error checking
- Receiver autonomy greater than one year
- All current receivers detect all Transmitters

The capabilities above, along with an installed base of over 8,000 compatible receivers, create a huge potential for infrastructure and data sharing which is just starting to be exploited.

2. VEMCO Pulse Interval Coding Overview

2.1 Current VEMCO Coding (R64k)

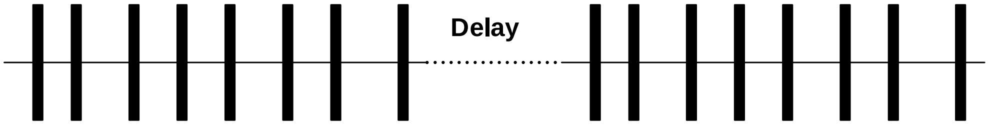


Figure 2-1: VEMCO R64K Pulse Interval Coding

The current VEMCO transmitter coding is referred to as R64K as it provides 64,000 unique IDs. The coding scheme shown in Figure 2-1, uses eight pulses to transmit the code. The coded information is contained within the intervals between the pulses. Typically a code transmission is followed by a long silence (called Delay).

Traditionally, VEMCO has used two other coding schemes – one with five intervals (R256) and one with six (R04K); but as the demand for unique ID codes has increased, it has become necessary to supplant these with R64K schemes.

2.2 Code Spaces and Receiver Code Maps

More than one coding scheme can be used simultaneously with the receiver and we refer to each scheme as a **Code Space**[1]. Table 2-1 shows all the Code Spaces currently supported by VEMCO.

Code Space	Coding Type	Notes
A69-1008	R256 -pinger	Limited use – mainly for VR1 users
A69-1204	R04K – pinger	Limited use - being phased out
A69-1206	R04K – pinger	Limited use - being phased out
A69-1105	**S256 – sensor**	**Current standard sensor tag type**
A69-1107	S256 –sensor	Limited use – being phased out
A69-1303	**R64K – pinger**	**Current standard pinger tag type**

NOTE: The majority of tags being sold in 2007 and beyond will be A69-1303 for coded pingers and A69-1105 for coded sensor tags. The other tag types are being phased out and their code space will be supplanted by R64K code spaces to allow for more IDs.

Table 2-1: Code Spaces Currently Supported by VEMCO

A feature of the unambiguous Code Space nomenclature is that the A69-XXXX designation is all a receiver needs to properly decode transmission and define it to database software.

Receivers are configured through a **Code Map** which describes a collection (usually four) of Code Spaces that it will be able to detect and decode. Details on currently supported Code Maps and selecting the right one for a particular study can be found here while information on how to configure a receiver is found in the VUE Software Manual.

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[1] In 2007, this terminology replaced the previous Sub Map terminology which was ambiguous with the consequences that receiver configuration errors could occur and data sharing was difficult.

2.3 Unique World Wide IDs and 64K Sensor Codes

Prior to 2006, when the majority of transmitters were coded in R256 and R04K Code Spaces we used duplicate tag IDs but assigned them to different geographic regions. As the demand for transmitters increased, this became increasingly difficult to make work. Therefore, starting in 2006, VEMCO committed to assigning unique IDs worldwide so that no matter where a tagged fish is detected, there is no ambiguity on its identity.

As part of the unique ID initiative, we have introduced a new coding scheme for Sensor Tags referred to as S64K coding. An S64K coded tag alternately transmits an R64K ID uniquely identifying the transmitter and an S256 code which contains an ID between 1 and 256 along with the sensor data as illustrated in Figure 2-2.

Single Pressure Sensor
R64k S256$_P$ R64k S256$_P$ R64k . . . .

Pressure and Temperature Sensor
R64k S256$_P$ R64k S256$_T$ R64k S256$_P$ R64k . . . .

Figure 2-2: S64K Transmission Sequence

In a simple migration situation, one simply uses the R64K ID to identify the fish and the S256 code provides the sensor data.

The situation is a little more complex in residency situations but the general approach is the same. When an S256 code is detected amongst the various fish, one searches for occurrence of a R64K ID which has been assigned to a sensor tag. This determines which fish the sensor data belongs to. This approach will work perfectly unless two tagged fish simultaneously appear having the same S256 ID code. Two observations can be made with respect to such occurrences:

1. The probability of it occurring will be low since VEMCO will continue to assign S256 ID codes to maintain as much geographic separation between duplicates as possible.
2. Even if the situation does occur, one still knows uniquely (from the R64k ID Codes) which fish were present. It just may not be possible to log the sensor data for the time that the particular tags are simultaneously present.

2.4 Blanking and Delay

Because of the low velocity of sound, acoustic telemetry systems need to deal with echoes arriving at the receiver long after the direct signal. An echo is a copy of the transmitted signal, caused by a reflection of the signal off of a surface such as the ocean floor, surface of the water, rock formations etc. Figure 2-3 shows a typical situation and, as can be seen, the receiver needs to be blanked (stop listening) for some time after detection of a pulse in order to ignore echoes.

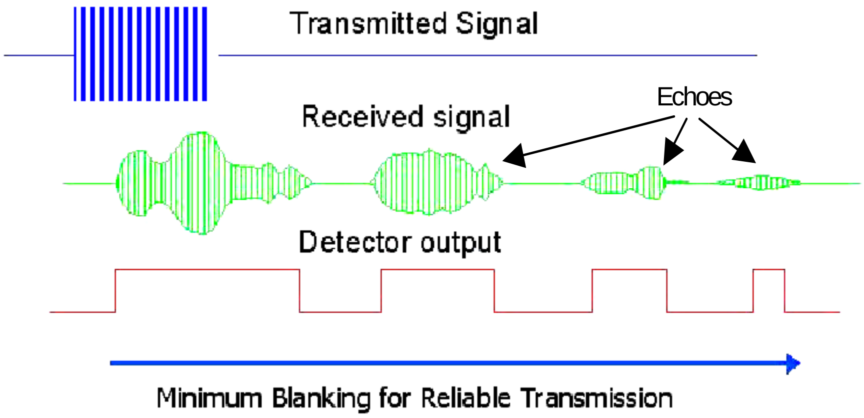

Figure 2-3: The Need for Receiver Blanking

In order to ensure reliable decoding in strong echo situations all transmissions use intervals 300 milliseconds or longer so that Blanking can be on the order of 250 milliseconds. The implication of this is that it will take roughly 3 to 5 seconds to complete a tag transmission.

Transmitters, once a code is transmitted, cease transmitting for a factory-set interval called **Delay** which serves two purposes:

1. Prolongs battery life
2. Makes it possible for multiple tags present at a receiver to all be detected

Delay[2] is typically set in the range of 30 seconds to several minutes. One can see the impact of longer Delay on battery life in the individual Transmitter Family (V7, V9, etc.) data sheets which can be accessed on the Coded Transmitters Page of the VEMCO webpage. In the next section we will show how the choice of Delay affects the ability to detect multiple tags.

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[2] Delay is actually randomized about a mean. Randomization about the mean is uniform and typically +/-50% (e.g. If mean delay is 60 seconds, the minimum is 30 seconds and the maximum 90 seconds).

3. Detection Times and Rates

3.1 Collisions and the Influence of Tag Delay

A collision between tags occurs when two or more tags transmit simultaneously such that some portion of their transmission overlaps. Figure 3-1 shows a typical collision scenario where the 2nd transmissions from transmitter 1 (T1) and transmitter 2 (T2) overlap. Such collisions result in failure to detect one or both codes[3].

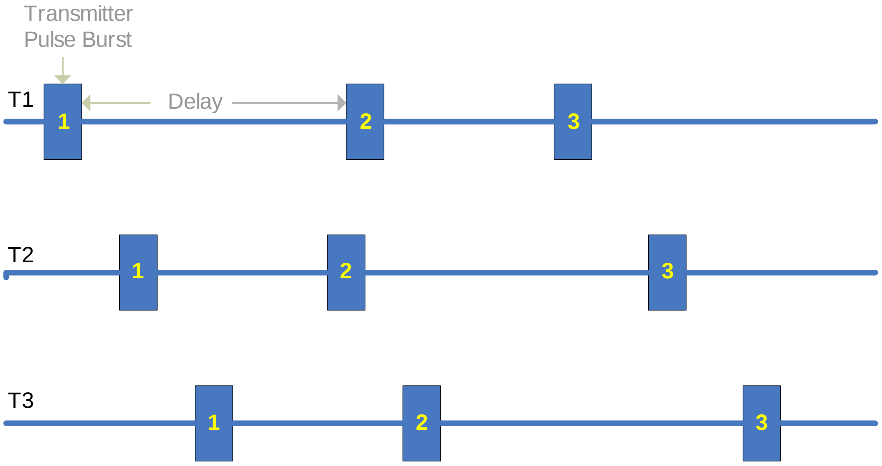

Figure 3-1: Simple Collision Situation Involving Three Transmitters

Note in Figure 3-1 that the Delay for each transmitter is not the same from one transmission to the next. All VEMCO transmitters randomize the delay in this fashion so that if two transmitters collide at a particular time, they will not on the next transmission. This feature is critical to the ability to deal with multiple transmitters.

Clearly, as more and more transmitters are present at a receiver, the collision rate will increase and, at some point, there will be so many collisions that few if any transmitted codes will be detected. A key point to note is that, in designing experiments, one needs to ensure that Delay is selected appropriately. In particular, choosing too small a value can have disastrous effects. For example, consider an experiment in which as many as 10 tagged fish could be present at a receiver. Using the tools described below, one can obtain the performance specifications shown in Table 3-1 where Residency is just the number of fish simultaneously present at a receiver.

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[3] Usually both.

Residency (# of tagged fish)	Average Time Between Detections of Each Tag (minutes)	
	Delay = 60 sec	Delay = 120 sec
5	1.5	2.5
10	2.6	3.2
20	8	5.6
30	24	9.7
40	73	17

Table 3-1: Effect of Delay and Residency on Time to Detect Each Tag

Table 3-1 highlights two important trends:

1. Shortening the Delay with the objective of getting more detections can have the opposite effect – better performance is achieved with 120 seconds than 60 once the residency exceeds 10.

2. Performance becomes disastrous if residency is too high for the Delay. For example, with a Residency of 50 tagged fish, each transmitter will be detected on average only once every 3.5 hours with a delay of 60 seconds – i.e. 99.5% of transmissions are lost due to collisions.

The remainder of this chapter will provide an overview of performance expectations. The reader can explore in detail what to expect for any scenario by using the On Line Collision Calculator, available on the VEMCO website which implements the analysis described below.

3.2 Note on Analysis Tools

All detection time presented are based on a 95% probability. For example, a statement that all n tags will be detected in x minutes should be read “n tags will be detected in x minutes 95 times out of 100.”

3.3 Time to Detect Individual Tags

It is a simple matter Figure 3-2 shows how detection times vary with delay from which one can see that if residency is large, performance improves dramatically as Delay is increased. The price one pays for this is increased detection times for low residencies as illustrated by Table 3-2.

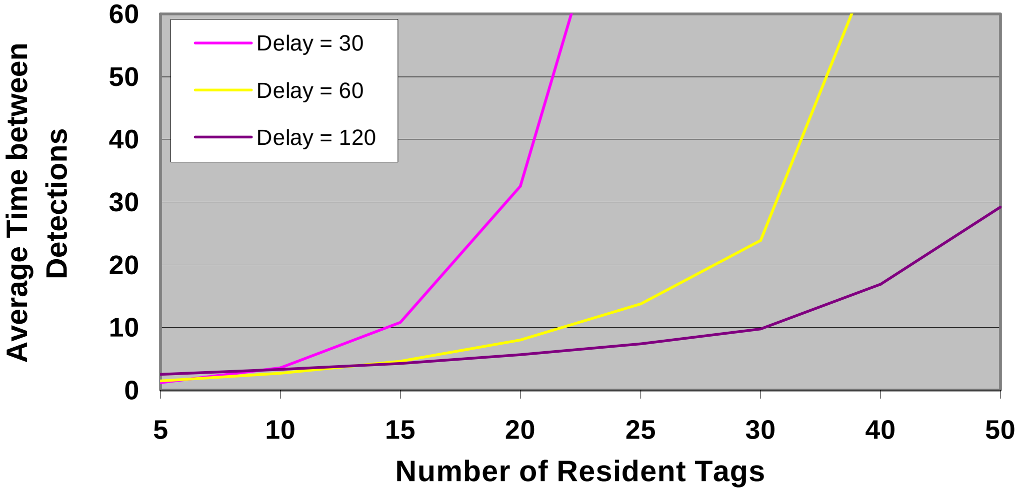

Figure 3-2: Detection Rate (minutes between detections) for Individual Tags

Residency (# of tagged fish)	Delay		
	30 sec	60 sec	120 sec
1	0.5	1	2.0
2	0.6	1.1	2.1
5	1.2	1.5	2.5

Table 3-2: Detection Rate (minutes between detections) for Individual Tags

3.4 Time to Detect All Tags

As delay is random, the fact that each of five tags is being detected at an average rate of once every x seconds does not mean that it takes x seconds to detect them all. If we start a test at time 0, some will be detected in less than x seconds; others will take longer. This effect is illustrated in Figure 3-3. Comparing this to Figure 3-2, one sees that the length of time to detect all is considerably longer than the average time between detections of the individual tags.

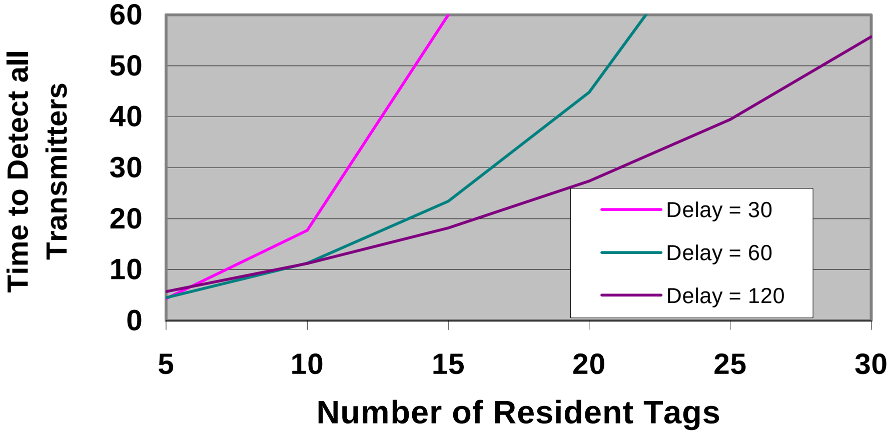

Figure 3-3: Time (minutes) to Detect All Resident Transmitters

Table 3-3 summarizes the performance one can expect for various choices of Delay.

Delay (seconds)	Minutes to Detect 3 Resident Tags	Maximum Residency Number for all Tags to be Detected	
		Within 1 Hour	Within 3 Hours
30	1.9	15	20
60	2.6	22	31
90	3.1	27	41
120	3.6	31	48
180	4.7	36	61
240	5.6	38	70
300	6.5	40	78
450	8.7	40	91
600	10.7	38[4]	99

Table 3-3: Summary of Performance to be Expected for Various Values of Delay

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[4] The explanation for this fall off is that the length of the Delay (10 minutes) is starting to become significant compared to the measurement period (60 minutes).

From the above, one can see that through the proper choice of Delay, one can in fact deal with a large number of resident tags. Table 3-4 summarizes trade offs in the choice of Delay. If the cases (upper right of Table 3-4) cannot be ruled out by the design of the experiments. Spread Spectrum approaches (Table 1-1) are required.

	Low Residence Number	**High Residence Number**
Short Residency Time	Set Delay to ensure fish detected for Shortest anticipated Residency time	No suitable compromise in extreme cases.
Long Residency Time	Delay not Critical	Set Delay to ensure acceptable detection rate for highest anticipated Residency Number

Table 3-4: Guidelines for Choosing Delay

3.5 Sensor Tag Considerations – Collisions and Data Update Rate

As described in section 2.3, a sensor tag using S64K coding will alternate between a pinger ID (R64K) and a sensor ID with sensor data (S256). In other words, only half the transmissions contain sensor data. This presents the user with a trade-off between:

1. Accepting that such a decrease in data rate is not an issue, or
2. Halving the delay to restore the data rate to what would be achieved with S256 coding.

As described in the discussions above on delay and detection rates, the second choice is not practical if high residency situations are anticipated[5].

Impact on Collisions

A question many users ask is what effect the sensor tag coding scheme will have on collisions. To answer this note that, as long as one uses the same delay, the old S256 and the new S64K schemes have the same duty cycle and therefore there is no difference in the collision rate between the two schemes.

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[5] One can halve the Delay without significant impact if it is anticipated that only a small portion of Resident Tags will be sensor tags.

4. VR2/VR3/VR4 Range and Detection Characteristics

4.1 Purpose of this Section

The purpose of this section is to explain receiver performance to a level sufficient for users to be able to properly design their studies and interpret their results. In the following, we will refer to the VR2 for simplicity but the comments also apply to VR3s and VR4s as the receiving portion of these products is identical.

4.2 VR2 Receiver Detection Characteristics

The VR2 receiver was designed to achieve long life in a small package which enables the large scale world wide networks we are seeing today. To achieve this, certain performance trade-offs are made. Most importantly is that the VR2 (and like receivers) are affected by broadband noise.

Most receivers (e.g. VR60, VR100) are Narrow Band which implies that the only noise seen by the detector is in a narrow frequency range around the tuned frequency (+/- 1 kHz in the case of the VR60). The VR2’s threshold, on the other hand, is impacted by any noise within the bandwidth of its preamplifier – typically 20kHz to 100 kHz. The implication of this is twofold:

1. The VR2 is more impacted by Sea State Noise since this is higher at lower frequencies than at 69 kHz. In fact, at lower wind speeds, Sea State Noise has no impact on a Narrow Band receiver.

2. Man-made (e.g. Echo Sounders) and Biological (e.g. Snapping Shrimp) noise sources that would have little or no impact on a narrow band receiver can have a serious impact on VR2 detection performance.

4.3 What it Means in the Field

From the above, it becomes apparent that if one conducts long term range testing, **without the tag or receiver moving**, changes in noise and/or propagation conditions with time will cause detection rates to start falling off at R_{min} shown in Figure 4-1, where R_{min} is the Range limit under the worst noise conditions encountered.

Keeping in mind that the variations in the Range Limit are usually weather related, one can see that there is little variability in the Range Limit over short periods of time – i.e. changes would occur over hours or days rather than minutes.

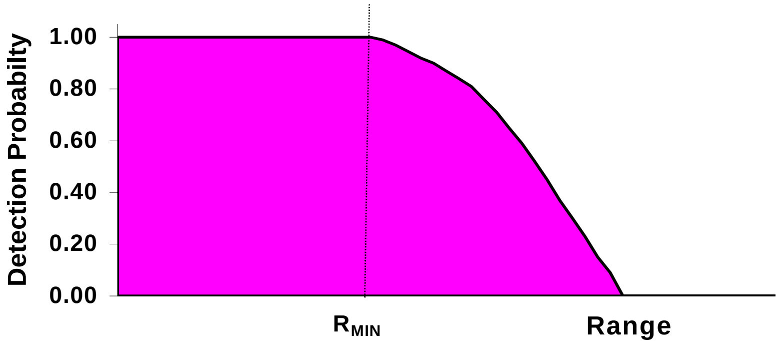

Figure 4-1: A Typical Result for Long Term Range Testing

This leads to the important conclusion with respect to using results like those shown in Figure 4-1 as the basis for an array design – i.e. that long term testing showing x% of transmissions are detected at a particular range **cannot** be interpreted to mean that x% of the transmissions from a tagged fish passing will be detected at that range. Rather, assuming that conditions for the study period are representative, it means that x% of the fish passing will have most or all of its transmissions detected – i.e. the fish will be within range for noise conditions at that time. The remainder will have few, if any, transmissions detected. Another way of saying this is that x% of the time, the noise conditions will be favourable for the animal to get detected at that range while the rest of the time, it's unlikely that any detections will be made due to the poor noise conditions most likely caused by weather.

4.4 Range Testing

Clearly, if the objective of a deployed receiver array is to provide 100% coverage of an area or 100% detection of fish passing an "Acoustic Gate", it is critical that the effective range of the receivers be known for all anticipated situations. To assist with this, VEMCO has developed, and is continuing to enhance[6], On Line Range Calculators which will predict range for typical ocean conditions. See Table 4-1 for typical results. However, given the number of factors that can influence range and their variability from one location to another, it is critical that **in situ** range testing be done if conditions are **suspected** to be different from those in normal ocean conditions.

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[6] Models for the VR2 are complex and we expect to make improvements over time.)

Sea State	Wind Speed (Knots)	Range SL = 142 dB	Range SL = 148 dB (V9H)	Range SL = 154 dB
0	Calm	418	564	729
1	4 to 6	403	548	710
3	11 to 16	302	429	577
6	28 to 34	199	301	429

Table 4-1: Calculated VR2 Range in Metres for 69 kHz Transmitter of Various Source Levels (db re 1 uBar @ 1 metre) in Normal Open Ocean Conditions

Guidelines for Effective Range Testing

User range testing should focus on areas and conditions of planned deployment and testing needs to be carefully planned in order to produce relevant results[7]. The following guidelines are recommended:

- Focus on determining Working Range – which we define as a range at which detection rate is close to 100% under all anticipated conditions. Referring to Figure 4-1, Working Range can be no greater than R_{min}.
- Collisions confuse things. Avoid them by using a single tag when range testing[8].
- Use tags with the same power output as tags to be used in the study. If buying a tag for range testing, VEMCO can measure the tag output power to select a tag close to the specification minimum. VEMCO can also provide a fixed delay tag specially configured for range testing.
- Analyze VR2 log to determine percentage of tags detected. This is easier if fixed Delay test tag used since one should be able to determine the fate of every transmission.

Recommended Procedure to Establish Working Range

The procedure outlined below is time consuming but gives the most rigorous results.

- Install VR2 in proposed or typical deployment situation. Clear the receiver log to make post testing analysis possible.
- Choose a starting range and place Tag in a fixed location and at a depth where fish are anticipated to swim.
- Allow Receiver to detect long enough that representative conditions are encountered (e.g. variations in weather). This would be at least several days.
- Repeat for other representative depths – and directions if this might be significant.
- If detection rate is 100% or very close to this, use this as Working Range or try further out.
- If detection rate below 100%, move in closer and repeat.

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[7] VEMCO will be happy to provide data on what to expect in normal ocean conditions.

[8] Or through the use of special fixed delay range testing tags which can be configured to eliminate collisions.

If results are disappointing, keep in mind that deployment location or depth might be the problem.

As a final comment, if the above procedure or a variant of it is considered to be too time consuming, it is critical that the testing either includes the worst conditions under which the systems are expected to operate or that an allowance is made for the fact that worse conditions will occur.

4.5 A Controlled Range Test Conducted by VEMCO

VEMCO carried out comprehensive detection testing in Shad Bay, Nova Scotia (far from open ocean conditions). A number of receivers were used in various locations and deployment depths and testing was typically conducted with transmitters at each range for one week or longer. An overview of results from a representative receiver is shown in Figure 4-2 where the data points represent the percentage of transmissions successfully detected at each range for which data was gathered. As can be seen, the detection characteristics are similar to those shown in Figure 4-1. In Figure 4-2, the increase in performance at 550 metres, while surprising at first glance, is explained by the fact that weather conditions were better during the time the transmitter was at this range. Based on these results, we would conclude that our working range is approximately 425 meters.

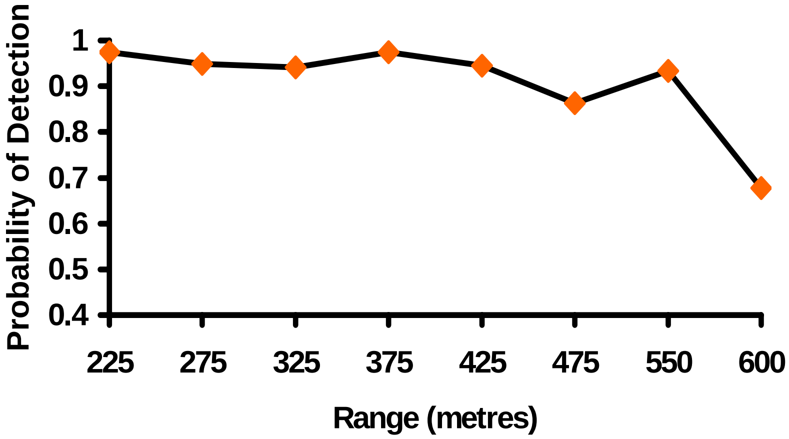

Figure 4-2: Typical Range Testing Results from Shad Bay, Nova Scotia

We can now examine some of the details behind the data of Figure 4-2 to substantiate that declining detection rates at longer range is a result of long term changes in background noise level rather than short term variability in performance. Figure 4-3, which shows results at a range of 275 metres, is illustrative. The average detection rate value at this range in Figure 4-2 is 94.9% but, in Figure 4-3 we see that, for a significant percentage of time, the Detection Probability is well over 95% but, on the other hand, there are periods when it drops significantly below that. The two periods of poorest performance represent the two most extreme wind/rain conditions during this test and the rain was significantly heavier during the second, lower performance period.

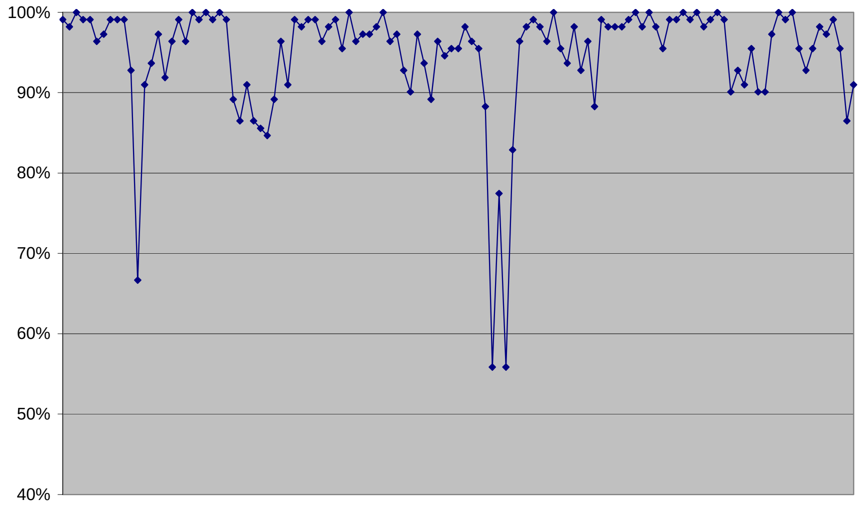

Figure 4-3: Detection Probabilities at 275 metres with Each Data Point Representing One Hour During which 110 Transmissions Took Place

Table 4-2 presents a brief summary of the data for this receiver and tag at all ranges over the two month test period. With the exception of the results at 550 metres discussed above, the general trend as range increases is a decrease in the percentage of time in which Detection Probability is high and in the minimum Detection Probability observed.

Range (metres)	Percent of Test periods with Detection Probability >0.95	Minimum Detection Probability
225	84%	0.85
275	71%	0.65
325	67%	0.5
375	88%	0.85
425	62%	0.65
475	59%	0.1
550	70%	0.3
600	16%	0.5

Table 4-2: Detection Probability Summary for Shad Bay Test (September 25 to November 25, 2006)

4.6 Detection Failures Not Related to Range Limitations

Less than close to 100% Detection at short ranges should be treated as a red flag that there is an issue related to the local noise or propagation conditions and, unless the situation is remedied, study results may be unacceptable. Methods to determine which one is the cause as well as suggestions for remedial action will be provided in an upcoming Application Note.

5. Comments on Future Directions

In this paper, we have highlighted some issues related to the performance limits of single frequency acoustic telemetry and the VR2 and VR3 receivers. To reemphasize a point, these limits arise as a trade off for the benefits of the system approach taken – namely, the ability to provide tracking solutions incorporating a wide range of transmitter options including very small, long life option and easily deployable, low cost, long life receiving systems.

At the same time, one of the goals of our research and product development activity is to raise the bar on the various performance limits mentioned above.

A key consideration in any new product introductions is recognition of important legacy issues such as the facts that:

- Existing VR2s (of which there are 1000s in the field) cannot be reprogrammed to recognized new, different single frequency schemes which could, for example, provide a more effective way of coding sensor data

- While VR2Ws, VR3s and VR4s can be programmed for new single frequency coding schemes, neither they nor VR2s will be able to recognize any spread spectrum signaling scheme.

This does not mean that we will avoid introducing new single frequency schemes and spread spectrum approaches where appropriate and necessary to meet users needs. However, every effort will be made to delay obsolescence of existing products as long as possible. For example, the objective is for future spread spectrum tags to be detectable by existing VR2s with performance consistent with that described in this paper and enhanced performance provided by a new family of spread spectrum receivers.