



What's The Maximum Range?

Physics of sound propagation in water.

You are considering buying a DiveTracker system to measure the water level of a very deep fresh water lake by placing a transponder at the bottom of the lake and interrogating it from the surface. After explaining the application to a Desert Star Systems engineer, you are informed that you should be able to reliably measure the separation between the two stations to a depth of as much as 14 kilometers. After you have completed the lake project, you mount the transponder on an underwater vehicle in order to track it in a shallow harbor. To your surprise, tracking starts turning unreliable on occasions at distances of as little as 100 meters - not even 1% of the range you got in the lake! After returning the 'defective' hardware to Desert Star for repair, you are informed that there is nothing wrong with it. So what happened?

The maximum range of any sonar based system depends on many factors. Some of these factors are equipment specific and can be controlled by the manufacturer. However, range is also severely affected by mother nature - the physics of sound propagation in water. This paper will give you a better idea of what to expect.

Table 1: 'Shallow Water/Horizontal Path' Range
(Spreading Loss = $\text{Range}^{2.5}$, Range In Meters).

Station Pair	Quiet Fresh Water Lake	'Typical Noise' Ocean	'High Noise' Ocean / Harbor
Station #1: STM-1,RBS-1,RBS-2, VLT-1,VLT-2,EM-2 Station #2: DS-1,(DT1-D-S), DT1-R-S,DT1-DRY, EM-1	700 (2000)	400 (900)	100 (200)
Station #1: STM-1,RBS-1,RBS-2, VLT-1,VLT-2,EM-2 Station #2: STM-1,RBS-1,RBS-2, VLT-1,VLT-2,EM-2	2000 (4000+)	600 (1250)	100 (300)
Station #1: STM-1,RBS-1,RBS-2, VLT-1,VLT-2,EM-2 Station #2: TLT-1	1250 (4000)	400 (900)	100 (200)
Station #1: DS-1,(DT1-D-S), DT1-R-S,DT1-DRY, EM-1 Station #2: DS-1,(DT1-D-S), DT1-R-S,DT1-DRY, EM-1	500 (1500)	400 (800)	100 (200)

notes:

- 1.Ranges in meters
- 2.First range number (no parenthesis) is the maximum range for reliable operation (12 dB S/N)
- 3.Second range number (in parenthesis) is the range at which the system becomes unusable (0 dB S/N)

Table 2: 'Deep Water / Vertical Path' Range
(Spreading Loss = Range2, Range In Meters).

Station Pair	Quiet Fresh Water Lake	'Typical Noise' Ocean	'High Noise' Ocean / Harbor
Station #1: STM-1,RBS-1,RBS-2, VLT-1,VLT-2,EM-2 Station #2: DS-1,(DT1-D-S), DT1-R-S,DT1-DRY, EM-1	4000 (4000+)	1000 (2000)	200 (600)
Station #1: STM-1,RBS-1,RBS-2, VLT-1,VLT-2,EM-2 Station #2: STM-1,RBS-1,RBS-2, VLT-1,VLT-2,EM-2	4000+ (4000+)	1250 (2500)	300 (900)
Station #1: STM-1,RBS-1,RBS-2, VLT-1,VLT-2,EM-2 Station #2: TLT-1	4000+ (4000+)	1000 (2000)	200 (600)
Station #1: DS-1,(DT1-D-S), DT1-R-S,DT1-DRY, EM-1 Station #2: DS-1,(DT1-D-S), DT1-R-S,DT1-DRY, EM-1	2000 (4000+)	1000 (2000)	200 (600)

notes:

- 1.Ranges in meters
- 2.First range number (no parenthesis) is the maximum range for reliable operation (12 dB S/N)
- 3.Second range number (in parenthesis) is the range at which the system becomes unusable (0 dB S/N)

Tables 1 and 2 summarize the range that is achievable using specific DiveTracker models and environmental conditions. First, decide if you are working in deep water with primarily vertical station separation, or in shallow water. Table 1 lists ranges for shallow water (horizontal) activity. Refer to table 2 for deep water / vertical jobs. Next, find the field in the table that specifies the DiveTracker model pair you expect to use and the applicable environment. The first number in the field specifies the maximum range at which communication and navigation should still be 'reliable'. The number in parenthesis is always a greater range. It specifies the maximum distance at which you will probably still get 'some' results.

Use the numbers from the range tables as a first step to get an approximate idea how far you will be able to go. In reality results will at times be slightly or even drastically better or worse. In the next section we will look at just what affects the sonar range and how the range tables are derived.

Tracing A Sonar Signal

Let's follow the path of a sonar signal from the transmitter to the receiver. The transmitter will emit a signal the strength of which is rather well defined. As the manufacturer, we can set the signal strength just about anywhere we please, but there are considerations of power consumption, equipment size and cost. Higher transmit power will result in greater power consumption, larger equipment size and a higher cost. Table 3 lists the sonar transmit

power for all DiveTracker models. The power is expressed in decibel (dB). Each increase by 3 dB means a doubling of the transmit power. Thus, the greater the number, the higher the transmit power. Naturally, higher transmit power results in greater range.

Table 3: Transmitter and receiver performance data for each model of the DiveTracker DTX family.

DiveTracker Models	DS-1 (DT1-D-S), DT1-DRY, DT1-R-S, EM-1 (DT1-MOD)	VLT-1, VLT-2, RBS-1, RBS-2, STM-1, EM-2	TLT-1
Sonar Transmit Power: dB re. 1 uPa @ 1 meter	180	185	180
Receiver Sensitivity: dB re. 1 uPa, 400 Hz Filter	101	90	90
Equivalent Noise Energy: dB re. 1 uPa per Sqrt(Hz)	75	64	64

notes:

- 1.All numbers are production acceptance standards and therefore represent 'worst case' for production hardware.
- 2.All numbers assume operation at 34 kHz to 41 kHz using the omni-directional transducer DT1-TDCR-40
- 3.Transmit voltage response for transducer is assumed to be 134 dB re. 1 uPa / Volt @ 1 meter (worst case transducer performance)
- 4.Transducer receive response is assumed to be -190 dB re. 1 Volt / uPa (worst case transducer performance)

After traveling through the water, the sonar signal will be received by a second DiveTracker. This DiveTracker has a certain, well defined receiver sensitivity which is also listed in table 3. The sensitivity is a measure of the maximum noise that is generated by the receiver itself. Internal noise is an undesirable but yet unavoidable reality of all receivers. The 'snow' that you see on a TV receiver tuned in between stations is a very visible manifestation of receiver noise. Just like transmit power, receiver noise is expressed in dB. In order for a sonar signal to be detected, it must be at least as powerful as the receiver noise. The relative strength of signal and noise is called the signal to noise ratio (SNR) and is expressed in dB. If a signal has the same strength as the noise, the SNR is 0 dB. If the signal has twice the energy of the noise, the SNR is 3 dB and so on.

By subtracting the receiver sensitivity from the transmit power, we can now obtain what we will call the signal strength operating budget. For example, the sonar signal that is transmitted by a STM-1 surface module is at least 185 dB strong. As it travels through the water, this signal will get progressively weaker. By the time it arrives at the receiver - say a model VLT-1 - it must be at least as strong as the receiver sensitivity, 90 dB in case of the VLT-1. Thus, we can afford to 'loose' up to 185 dB - 90 dB = 95 dB of signal strength and still be able to detect the now weakened signal. Unfortunately, detecting a signal with a 0 dB SNR will tend to result in marginal operation. For this reason a second number is listed in parenthesis. This reduced operating budget gives you a

SNR at the receiver of 12 dB, enough to ensure in most cases that at least 90% of position fixes and telemetry transmissions will succeed. The signal strength operating budgets for various DiveTracker model pairs is listed in the 'quiet lake' column of table 4. Keep in mind that the operating budget may be more in one signal travel direction than in the other due to differences in transmit power and receiver sensitivities of the DiveTracker models. In the case of dissimilar model pairs, the table lists the lowest available operating budget, i.e. the worst case.

Table 4: Signal-Strength 'Operating Budget' For Reliable (And Marginal) Performance.

Station Pair	Quiet Fresh Water Lake	'Typical Noise' Ocean	'High Noise' Ocean / Harbor
Station #1: STM-1,RBS-1,RBS-2, VLT-1,VLT-2,EM-2 Station #2: DS-1,(DT1-D-S), DT1-R-S,DT1-DRY, EM-1	84 dB (72 dB)	80 dB (68 dB)	60 dB (48 dB)
Station #1: STM-1,RBS-1,RBS-2, VLT-1,VLT-2,EM-2 Station #2: STM-1,RBS-1,RBS-2, VLT-1,VLT-2,EM-2	95 dB (83 dB)	85 dB (73 dB)	65 dB (53 dB)
Station #1: STM-1,RBS-1,RBS-2, VLT-1,VLT-2,EM-2 Station #2: TLT-1	90 dB (78 dB)	80 dB (68 dB)	60 dB (48 dB)
Station #1: DS-1,(DT1-D-S), DT1-R-S,DT1-DRY, EM-1 Station #2: DS-1,(DT1-D-S), DT1-R-S,DT1-DRY, EM-1	79 dB (67 dB)	79 dB (67 dB)	60 dB (48 dB)

notes:

- 1.First number represents maximum total signal loss that can be tolerated. A signal loss of this amplitude results in a 0 dB SNR at the receiver end.
- 2.Numbers in parenthesis represent total signal loss that can be tolerated without losing reliable operation. It assumes that a SNR of 12 dB is necessary for reliable operation.
- 3.Noise in 'Quiet Lake' is assumed to be 0 dB re. 1 uPa / Sqrt(Hz); S/N is limited by DiveTracker receiver internal noise
- 4.Noise in 'Typical Ocean' is assumed to be 74 dB re. 1 uPa / Sqrt(Hz)
- 5.Noise in 'High Noise Ocean / Harbor' is assumed to be 94 dB re. 1 uPa / Sqrt(Hz)
- 6.All numbers are worst case for the specified DiveTracker pair and sonar conditions.

It's A Noisy Place Down There...

Readers with teenage children (or teenage employees, for that matter) will appreciate the fact that while you may be able to hear a pin drop in your study, you sure can't do the same in your child's room. The problem isn't that your ears go bad as soon as you open the door but rather that the music is just too bloody loud! In effect, the 'transmit range' of the pin is drastically reduced in the teenagers room.

There is plenty of noise in the seas, and what's more the intensity of the noise is highly variable. Much noise has biological origins such as snapping shrimp or urchins. Other noise is man made or caused by wind, waves or rain. Some places like deep lakes tend to be very quiet. Others, like the immediate vicinity of active reefs, are usually very noisy. Then, there are many places where you simply cannot predict noise levels just by looking at them - such as harbors. Often you will be surprised to find for example that an outwardly quiet backwater is indeed far noisier than a stretch of open ocean on a rough day. The only way to be sure about noise levels at any given locale and at any given time is to measure it. DiveTracker equipment always includes noise measurement software, and any sonar man worth his salt will measure noise levels before starting tracking or telemetry operations.

In all but the quietest waters, sonar range will not be limited by receiver internal noise but rather the ambient noise which overwhelms it. In table 4, only the 'quiet lake' column assumes limitation by receiver noise. The other two columns reflect signal strength operating budgets that you might have at your disposal in a 'typical ocean' and at a really noisy place. For example, a STM-1 - VLT-1 combination gives you a budget of 95 dB (83 dB for reliable operation) in a quiet lake but as little as 65 dB (53 dB) in some noisy places.

How Big, How Fast A Loss?

Now that we have determined the signal strength budget available for a given DiveTracker pair and a given noise level, we are finally getting close to our estimate of distance. The issue that still needs to be resolved is just how fast the sonar signal will get weaker as it travels through the water, i.e. what range it will take to consume our signal strength operating budget.

It can be shown that in a completely uniform body of fresh water the sound will get four times (6 dB) weaker for each doubling of the distance. This is known as 'spherical spreading loss'. However, in the real world the signals often attenuate drastically faster while in other cases signal attenuation can actually be significantly less severe than predicted by this simple model. There are several major causes of this distortion.

In the real world, water is not uniform. Rather, it is stratified into layers of different temperature and salinity. Even a mixing of fresh and salt water may occur in some places. These 'density gradients' cause sound to be bend and even reflected. If the sound gets trapped at a certain depth, ducting occurs and you may find the range dramatically improved. However, even more likely the sound will get scattered around or reflected away from the receiver. Consequently, signal loss can be much faster. The effect of density gradients tends to be more of a problem for horizontal than for vertical transmission paths.

Sea water contains several chemicals that actually absorb sonar energy - turning it into heat. This effect which becomes increasingly severe at higher frequencies. DiveTracker operates at 34 kHz - 41 kHz. At these frequencies, the effect becomes noticeable at ranges of 500 meters or more.

Table 5: Signal Loss (Spreading Loss + Sound Absorption) As A Function Of Range At 40 kHz

Range	50	100	200	300	400	500	600	700	800	900	1000	1250	1500	1750	2000	3000	4000
F	17	20	23	25	26	27	28	28	29	30	30	31	32	32	33	35	36
F ²	34	40	46	50	52	54	56	57	58	59	60	62	64	65	66	70	72
F ^{2.5}	42	50	58	62	65	67	69	71	73	74	75	77	79	81	83	87	90
F ³	51	60	69	74	78	81	83	85	87	89	90	93	95	97	99	104	108
A	0	1	1	2	3	4	4	5	6	6	7	9	11	12	14	21	28
S	17	21	24	27	29	31	32	33	35	36	37	40	43	44	47	56	65
S ²	34	41	47	52	55	58	60	62	64	65	67	71	75	77	80	91	100
S ^{2.5}	42	51	59	64	68	71	73	76	79	80	82	86	90	93	97	108	116
S ³	51	61	70	76	81	85	97	30	93	95	97	102	106	109	113	125	136

notes:

1.Ranges in meters

2.Signal loss in dB

3.F: Total signal loss in fresh water assuming a spreading loss of range, range2 , range2.5 or range3 and 0 dB/km absorption

4.A: Signal loss due to sound absorption in sea water at a rate of 7 dB/km ('Sound Propagation In The Sea', Urick, Figure 5)

5.S: Total signal loss in sea water assuming a spreading loss of range, range2 , range2.5 or range3 and 7 dB/km absorption

Table 5 lists estimates for signal loss as a function of range. When operating in fresh water, refer to one of the 'F' rows. For salt water operations use the 'S' rows of the table. We recommend that you use the 'spherical loss' model (F2 and S2) when estimating ranges for vertical transmission paths. Use the less favorable F2.5 or S2.5 model when your transmission path is primarily horizontal. For real pessimists there is also a 'cubical loss' model (F3 and S3), while optimists who are certain that favorable ducting will always be available may use the 'linear loss' (F and S) model.

After selecting the appropriate signal loss model, just follow the applicable row until the indicated dB signal loss is about equal to the available signal strength operating budget. Look up the corresponding range at the top of the table.

A Summary Of Range Prediction

We started out this paper with the story of the disappointed customer who found he could track his underwater vehicle in a harbor only to a distance of about 100 meters or so. By looking at the tables, you will be able to tell what might have happened. Assume the customer was using a STM-1 surface module and a VLT-1 transponder aboard the vehicle. While table four reveals that this combination will give him an operating budget of 83 dB for reliable operation in quiet waters, it also shows that this budget might be reduced to as little as 53 dB if the harbor turned out to be very noisy. Had the customer operated in deep water, this may still not have been all that bad. Table 5 shows that 53 dB should be enough to get somewhere between 300 and 400 meters range in sea water if spherical spreading applies. However, the water in the harbor may have been highly stratified causing the S2.5 model to be more realistic than S2 and thus reducing the range to somewhere around 100 meters.

In most practical applications you are not very likely to find either end of the spectrum to be the reality. Rather,

you may achieve a range that lies somewhere in between the 'deep lake' and the 'shallow, noisy, stratified harbor' example. We hope however that this paper has cleared some of the 'fog' that often surrounds sonar range predictions.

Stretching The Limit...

The DiveTracker system features a highly versatile design, which in many cases can be adapted to obtain greater range. Here's a few things that we can do for you to 'stretch the limit'.

For vertical and some horizontal transmission path applications, DiveTracker can be outfitted with directional transducers. These transducers can increase range very significantly but require some degree of 'pointing'.

For salt water applications that demand ranges of 1 km or more, consider asking us to equip your system with sonar transducers that operate at lower frequencies. Low frequency transducers are far less affected by salt water sound absorption. However, they are also bulkier and have a higher cost.

When operating in high-noise environments, it is advantageous to use a narrower receiver filter which will filter out more of the ambient noise. However due to the 'Doppler effect' this will also reduce the relative speed at which the two stations can travel. The standard filter allows for a relative speed of up to 13 knots. A second detrimental effect of a narrower filter is that tracking accuracy will suffer and telemetry speeds will be reduced.

We may also be able to increase transmit power in some cases. Of course, this will shorten battery life and the distance advantage may be insignificant.

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