Precision at Speed

How To Track Fast Moving Underwater Vehicles

David Kronen of Florida Atlantic University (FAU) was puzzled. He was using a three-transducer DiveTracker™ short baseline system to navigate the University's AUV into its docking station. Position fixes were good whenever the AUV was standing still. But as soon as the AUV picked up speed, position fix quality went to hell. The result looked like the plot in figure 1. A reasonable vehicle track at low speed but awful zig-zagging whenever the vehicle was cruising.

It didn't make any sense. Stationary tests in pools and the ocean had shown DiveTracker™ to have a range measurement repeatability of as good as 5 to 12 centimeters - much better than needed to get the job done. And those numbers were pretty solid. Independent tests by the Naval Postgraduate School and Desert Star Systems had yielded similar results. Accuracy tests by Scripps Institute (UCSD) had shown the system to be more accurate than their best available standard - a sub-meter differential GPS.

It turns out there's more to positioning accuracy than just the system's ability to precisely measure range. The baseline transducer separation is of course important. A shorter baseline means less accuracy, a longer baseline results in better accuracy (see application note #DTAN-004 'Ultimate Precision'). However, even more important for moving vehicles is the choice of a suitable 'pinging protocol'. 'Pinging protocols' are DiveTracker's way of finding a position. In essence, a navigation cycle is initiated by a station (surface station or vehicle) sending out a sonar interrogate signal. This signal travels to the other stations in the network, which reply with their own signal. By measuring the time it takes for signals to bounce between the various stations, distances are determined. A little geometry then yields the vehicle position. DiveTracker™ supports dozens of pinging protocols, each having its own set of advantages and limitations. Some pinging protocols are hardly affected by vehicle speed. In others speed is the accuracy limiting factor at anything faster than a fraction of a knot. Let's take a look.

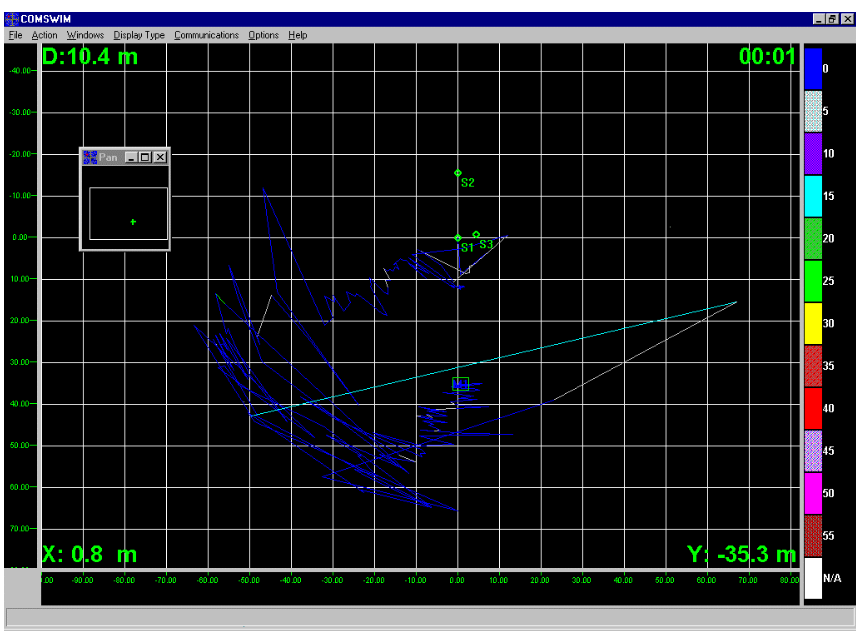

Figure 1: A Vehicle Track Degrades at Higher Speeds

Figure 2 shows two pinging protocols. On the left is a three-transducer short baseline (wired baseline transducers) configuration. On the right is a pinging protocol for a three-transducer long baseline setup. The short baseline navigation cycle starts with S1 (surface transducer 1) transmitting a ping or an address code (#1). The ping travels to the AUV, which replies (#2). The reply travels back to S1. At this time, the **surface**

station knows the distance between S1 and the AUV. The surface station now sends another ping out of S1, which again travels to the AUV (#3). The AUV replies and the reply is received by S2 (#4). So now, the surface station knows the S1→AUV→S2 distance. It subtracts the previously known S1→AUV distance and thus obtains the S2→AUV distance. The cycle is continued to determine the distance between S3 and the AUV (#5 and #6). (The math works out so the AUV will also know the distances to S1, S2 and S3 after it receives ping #1 of the next navigation cycle).

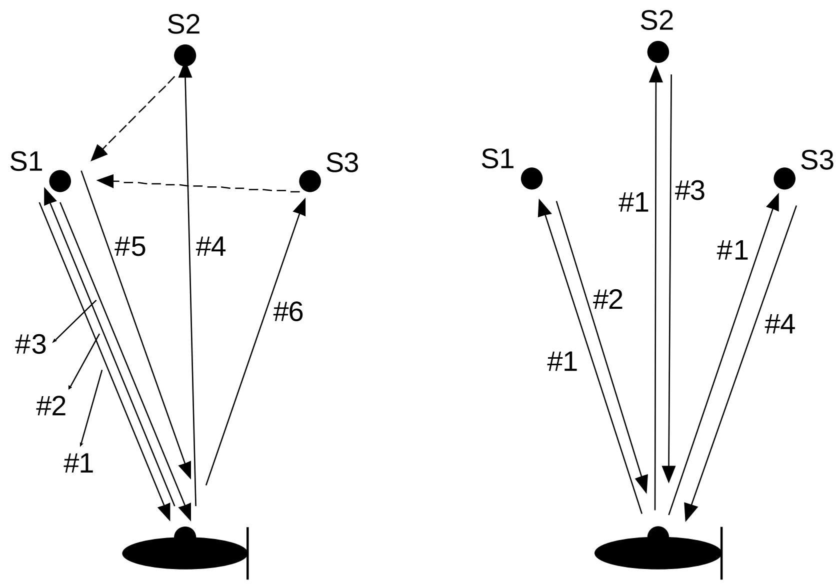

Figure 2: A Short Baseline and A Long Baseline 'Pinging Protocol'

The problems start when the AUV moves. Take a look at figure 3. The AUV is moving towards the baseline transducers. The short baseline pinging protocol results in the S1→AUV distance being measured first (d1). By the time, the S3→AUV distance is fixed (d3), the AUV has moved a significant amount. This move skews the position triangle, and the AUV now appears to be in a different position and heading into a different direction.

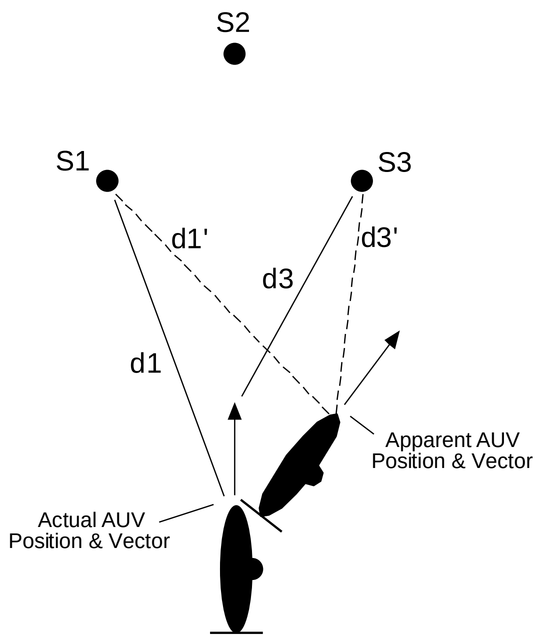

Figure 3: Vehicle Speed Can Introduce Positioning Errors

As the AUV moves faster, it covers a greater distance between the AUV→S1 measurement and the AUV→S3 measurement. Consequently, the error grows. The total error depends on other things as well. AUV heading plays a role and so does the distance and relative position of the baseline stations. Ultimately however the speed error is caused by the simple fact that all distance measurements do not take place at the same time.

Reliable Positions At Any Speed

If the AUV's distance from all baseline transducers could be measured at the exact same time, there would be no speed related position error. For reasons of hardware limitations and the very nature of sonar technology and physics, this can't be done. Fortunately, we can get very close. The drawing on the right of figure 2 shows an AUV finding its position by means of long baseline navigation. The AUV sends out an interrogation ping or code (#1) which travels to all baseline stations. Each baseline station replies after waiting a slightly staggered amount of time (#2, #3, #4).

In a typical scenario, the reply of baseline station #3 follows just 0.2 seconds after the reply of station #1 (the delay of station #2 relative to #1 is 0.1 seconds). This compares to the three-transducer short baseline case where the delay between the measurement of the distance to S1 and the distance to S3 can run from 0.6 seconds to more than 1.9 seconds. On this account alone, the speed induced accuracy degradation of the short baseline protocol is far worse than it is for the long baseline case. A closer look reveals another significant difference.

The short baseline protocol determines the S3→AUV distance by subtracting the previously measured S1→AUV distance from the S1→AUV→S3 round-trip time. Assume the S1→AUV distance was measured as 100 meters. By the time S1→AUV→S3 is measured, the AUV has moved 3 meters. So, the round trip distance is measured as 97 m + 97 m = 194 m. The original S1→AUV distance of 100 meters is subtracted, and the apparent S3→AUV distance is found to be 194 m - 100 m = 94 m. Despite an AUV movement of only 3 m, S3→AUV is found to be 6 m shorter than S1→AUV! The error has doubled!

Now let's look at the similar long baseline case. At the time of the interrogation, the AUV is 100 meters away from the baseline stations. This interrogation goes to all three-baseline stations. By the time the AUV receives the reply from S3, we assume it has once more moved 3 meters and is now 97 meters away. Thus, it sees the AUV→S3→AUV round trip length as 100 m + 97 m = 197 m. The AUV→S3 distance is computed to 197 m / 2 = 98.5 m. While the short baseline approach doubled the error introduced by a given time lag, the long baseline method cuts it in half. This amplifies the performance difference between the two protocols by another factor of four!

Table 1 puts some numbers on our study. The first column lists several protocols. In the second column you'll find the maximum recommended speed for that protocol. We define the maximum recommended speed as that point where the speed induced range measurement error is equal to our published 15 cm (6") RMS error for any range measurement. At speeds higher than the recommended maximum, the overall position error is speed dominated. The last column lists the speed induced position error you would expect to see at a 'docking speed' of 1 knot when operating within the triangle bounded by the three baseline stations or transducers. Please keep in mind that these numbers are first order approximations only. They assume that all baseline stations or transducers are located at essentially the same place and that the vehicle is moving either directly towards them or directly away from them. In real life, the numbers may be slightly larger or smaller.

Configuration	**Typical Application**	**Max. Speed**	**Error @ 1 Knot**
3 Transducer SBL, Speed 1 Interrogate & Telemetry, Tracking & Navigation 0 meter range	AUV/Diver Tracking & Nav	S: 0.18 knots V: 0.29 knots	S: 0.84 m V: 0.51 m
3 Transducer SBL, Speed 1 Interrogate & Telemetry, Tracking & Navigation 500 meter range	AUV/Diver Tracking & Nav	S: 0.07 knots V: 0.08 knots	S: 2.17 m V: 1.84 m
3 Transducer SBL, No Telemetry, Ping Interrogate, Tracking & Navigation, 0 meter range	AUV/Diver Navigation	S: 0.35 knots V: 0.35 knots	S: 0.42 m V: 0.42 m
3 Transducer SBL, No Telemetry, Ping Interrogate, Tracking & Navigation, 500 meter range	AUV/Diver Navigation	S: 0.08 knots V: 0.08 knots	S: 1.75 m V: 1.75 m
3 Transducer SBL, Speed 1 Interrogate & Telemetry, Track Only, Any Range	ROV/AUV/Diver Tracking	S: 0.54 knots	S: 0.28 m
3 Transducer SBL, No Telemetry, Ping Interrogate, Tracking Only, Any Range	Slant Range Tracking	S: 1.50 knots	S: 0.1 m
3 Baseline LBL, No Surface Station, Any Range	AUV/Diver Navigation	V: 3.00 knots	V: 0.05 m
3 Baseline LBL Plus Surface Station, Any Range	AUV/Diver Tracking & Nav	S: Unlimited V: 3.00 knots	S: 0 m V: 0.05 m

3 Transducer SBL Using STM-2 Surface Station, S. 1 I. & T., Tracking Only	ROV/AUV/Diver Tracking	S: Unlimited	S: 0 m

Notes:

- Vehicle moves directly towards or away from closely spaced baseline stations or transducers.
- Based on measured difference between first and last range.
- At 'Max. Speed' the speed induced range error is equal to DiveTracker's published RMS range measurement repeatability of 15 cm (6").
- Error @ 1 Knot indicates the range error when the vehicle moves at a speed of 1 knot. This is also the max. approx. position error when moving within the triangle bounded by the three baseline stations or transducers.
- Max. speeds and errors indicated for the surface station perspective (S) and vehicle perspective (V).

Table 1: Max. Recommended Speeds And Position Errors For Various Network Configurations

Table 1 shows a vast difference in the performance of the network configurations at speed. A short baseline system with three transducers configured for both surface tracking and vehicle navigation is the worst. The accuracy of this configuration becomes speed limited at speeds of 0.18 knots at small range, then degrades even further as range grows. Other configurations don't show speed based degradation below three knots - or any speed. In summary, the choice of an inappropriate protocol can result in even an AUV trying to dock at idle speed as being too fast. On the other hand, a suitable long baseline configuration can track a submarine moving at 20 knots and still introduce a position error of only 1 meter. Figure 4 shows the track of a Phantom ROV moving in Mono Lake at speeds from 0 to just over 1.5 knots (vertical track at right side of screen). The ROV was tracked using a long baseline setup. The data shown is raw sonar data without any filtering or averaging. The resolution is 3 meters per division. Still, no accuracy degradation is apparent at any speed.

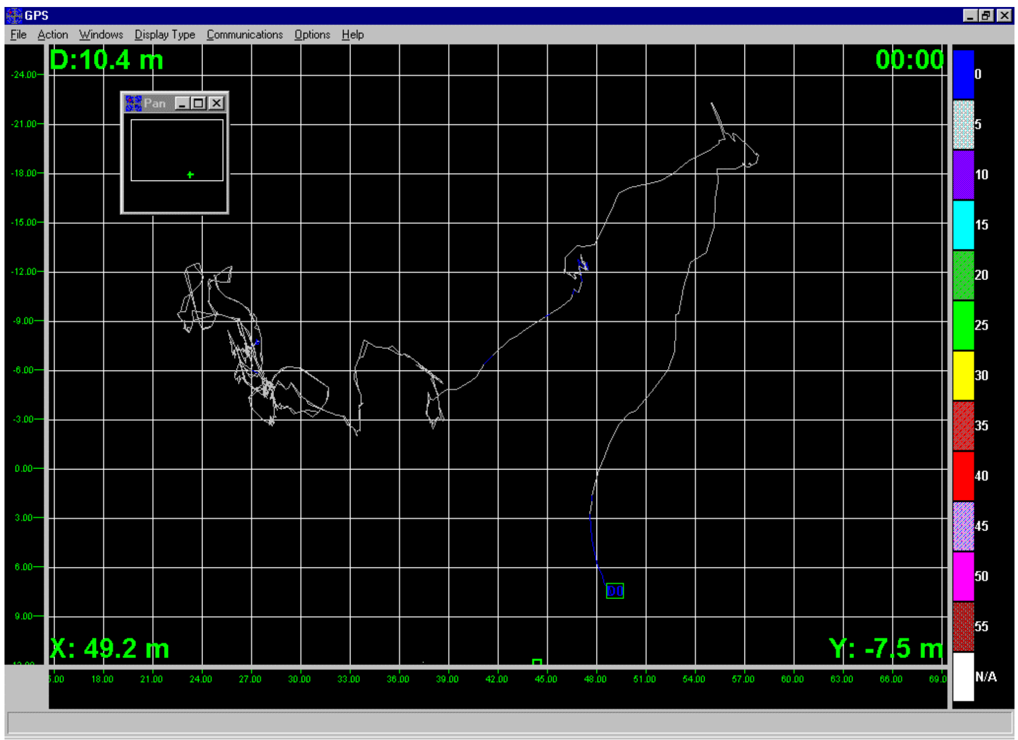

Figure 4: High-Resolution LBL Track of an ROV Moving at Speeds of Up to 1.5 Knots

Recommendations for Vehicle Tracking & Navigation

- Use LBL configurations for **navigating** fast moving vehicles. Do not use SBL configurations.
- SBL configurations are OK for tracking (not navigating!) vehicles or divers at moderate speeds.
- Maximize the size of SBL baselines. Short baselines amplify any error, speed caused or otherwise.
- For survey grade LBL navigation, place baseline stations in the corners of the survey area.
- For LBL docking applications keep baseline station separation between about 30 m and 100 m. This provides good accuracy at long range while not degrading position update rates due to excessive station spacing.
- Averaging position fixes over a sliding window of a few seconds improves accuracy at low to moderate speeds.

A Thank You to Our Customers

Since its introduction in 1994 DiveTracker™ has been used in exotic applications spanning the range from decompression computing for rebreathers to sonar telemetry through mud and - as described in this application note - AUV docking. The system's inherent flexibility certainly is a major reason for its popularity. Still, few of the system's capabilities and features would exist today if it weren't for our customers - your - extensive research and test. Many a times have we implemented your suggestions and the results of your research in order to make DiveTracker™ a better system for all our customers. We salute and thank you for this work - a work that at times surely is frustrating. Feel assured that we will always support you to make sure your investment in our products a worthwhile one.

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