A New Long Range Current Profiler

Development of the *Signature75*

Atle Lohrmann and Sven Nylund
Nortek AS
Oslo, Norway
inquiry@nortek.no

***Abstract*— When designing ADCPs, we trade off profiling range, vertical resolution and energy consumption. The last point is restricted by the availability of batteries and is usually fixed for a planned deployment. The first two points are intertwined in a complex relation because good vertical resolution requires both short acoustic pulses and a reasonably wide bandwidth, both of which lead to shorter range. As such, it is hard to reach any breakthrough in the range-resolution characteristics of an ADCP without finding a completely new approach to estimating velocity from the acoustic echo. Against this backdrop, our development of a new long range current profiler focused on optimizing each element in the system that we could control, from transducer design to mechanical design, from power consumption to profiling range, and from interfacing to data storage. Combined with a very flexible timing controller, this novel system provides the basis for a new generation of current profilers where the hardware platform is referred to as AD2CP, of which the Signature75 long range current profiler is the first fully commercial implementation. In a recent test outside Toulon France, the system functioned every bit as efficiently as we could have hoped and collected velocity data over a profiling range exceeding 900 meters in the Mediterranean.**

Keywords—ADCP; current meter; current profiler;

I. Introduction

Long range current profilers are deployed across the globe to measure currents in the open ocean. The main motivation is to understand and model the ocean circulation, which is an important driver for the redistribution of heat on our planet. The cross coupling between the ocean and atmosphere means that the circulation is responsible for some of the main weather patterns. During the last two decades, the focus on properly understanding the circulation has intensified because of the general interest in global warming, with special focus on the heat fluxes in and out of the polar seas.

In addition to the scientific interest in the general ocean circulation, the hunt for energy in ever-deeper water has generated an interest in understanding and predicting the forces that are acting on marine structures. This includes risers used by the oil industry to drill for oil or bring oil up to the surface. It also includes experimental extraction of energy from strong currents like the Gulf Stream offshore Florida.

Long range current profilers are not new to the market. RD Instruments first introduced a 75 kHz ADCP (Acoustic Doppler Current Profiler) in the 1980s and has since effectively enjoyed monopoly in this market segment. This temporary situation was in large part owed to the patent protection provided by US patent 5,208,785, [1] which describes a processing system for ADCPs where the processing lag is independent of the cell size (see section II.A for a more complete description). There are two reasons why the patent was particularly important for long range systems:

- The differential effect of transmit power on profiling range is quite significant so it is natural to design the system for maximum output power.
- When measuring below the wave boundary layer, the maximum velocities are smaller than for the higher frequency current profilers typically used in coastal environments.

The optimum solution is then to develop a high-power system that pings very rarely and relies on high-precision ping-sequences with low ambiguity velocity, which is exactly the opportunity that was afforded by the patent.

The US patent expired in 2010 (2011 overseas) but our development of a new generation of current profilers was delayed due to several detours into the realm of performance optimization for acoustic Doppler current profilers [2]. A series of left and right turns were thus attempted before a new long range current profiler could be brought to market.

II. Description

A series of choices had to be made before embarking on the development of a new generation of current profilers. Some of the choices were trivial and some were hard, but it all came down to the same issues: What can be done given our current knowledge about signal processing, transducers, electronics, and mechanics, and what are the limits we have to contend with?

A. Signal processing

One of the first tasks was to investigate the choice of signal processing schemes to implement. The transmit sequence used thus far is quite simple [3][4]:

- Transmit a pulse of a give wave form
- Wait for a time period T
- Transmit the same pulse one more time

- Wait for a time period T
- <Repeat as many times as desired>

The return echo from the water is processed for phase shift at a lag τ equal to the length of the transmit pulse plus the waiting time T. The goal is to come up with a bias-free estimate of the velocity profile and at the same time optimize the velocity precision, i.e. minimize the noise variance of the velocity profile. Even if simple in principle, the choices are many and only through a proper modeling effort was it possible to arrive at an optimum solution. While the details are beyond the scope of this paper, some of the key features are:

- Frequency coding of the transmit pulse rather than phase coding. This makes it possible to choose among a continuum of pulse lengths and allow the user greater choice in the instrument configuration.
- Modeling and testing correction algorithms to compensate for differential water absorption over the frequency band.

B. Transducers

Transducers transform the electrical energy generated in the transmitter to an acoustic pressure wave in the water. In receive mode it then senses the echo generated from particles in the water column and transforms the acoustic energy back into electrical energy that can be processed for velocity. Transducers are the sensing elements in a Doppler current profiler and we decided early on to make them larger than what has been commonly available at 75 kHz. The target was set at 25 cm (10”), which is large enough to bring the acoustic beam width below 5º. This is in the range of other current profilers operating at higher frequencies. This has the advantage of giving the system better acoustic directivity (about 3dB improved SNR), which has the same effect as doubling the output power. It also reduces the side lobes and thereby makes the system less sensitive to reflective surface in the vicinity of the main acoustic beam. However, a 25 cm broadband transducer cannot be made from a single element ceramic, so we turned to composite transducer design to solve the problem of making transducers that are larger, lighter, have good bandwidth, and are more sensitive in receive mode. A composite transducer is made from ceramic elements that are formed as small staffs that are equidistant and separated by a properly formulated epoxy resin (Fig. 1). As such, a single transducer can be made from several pieces of ceramic raw material that are glued together. Because design and production of composite transducer requires special skills and optimized machinery, the actual production takes place at Nortek Piezo in Aberdeen.

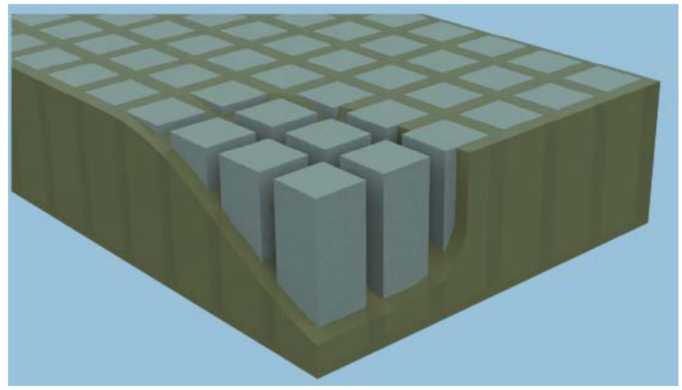


Figure 1 - In composite transducers, the transduction is performed by individual ceramic staffs that are free to move independently of each other.

In addition to the transducer design and construction, the tuning of the electronics turned out to be quite important both in transmit and receive mode. This is a commonly overlooked element in the design of underwater acoustic systems, most likely caused by the sheer complexity of tuning a circuit to something that does not have constant electrical properties across the frequency band. In the case of the Signature75, the transducer element has a bandwidth close to 40% although only a fraction of this is used in the processing algorithms.

We use three transducers for velocity measurements, as has been common in Nortek current profilers. Using three instead of four in this case has significant impact on production cost while still making it possible to check for non-zero vertical velocity, a QA/QC element that is standard in most software written to analyze current profiler data.

.

C. Data collection

In our long range current profiler, more than 90% of the power consumption goes to the transmit pulse and very little goes to processing and data storage. As a consequence, efficiency in the transmit/receive chain is paramount while a little extra processing or storing extra data is of little consequence to the overall power consumption. This allows the Signature75 to store every current profile as it is being collected, before it is averaged to form an ensemble current profile. QA/QC can therefore be conducted on individual data (“single pings”) in post processing to remove interference that has only affected one or more current profiles. This is especially relevant for removing interference from fish, which often are not sufficiently persistent to be seen in amplitude or correlation parameters but still can bias the velocity profile in either direction.

In addition to the standard data, the system will store the raw magnetometer data that is collected every time the compass direction is being read. From a practical point of view this means that any instrument that has spun at least 360 degrees during a deployment can be calibrated for hard iron effects in post processing. This avoids the problem of calibrating the compass before deployment and in principle makes it possible to achieve higher directional resolution in the current velocity data.

III. Multiple processors

The oceanographic industry has long hesitated to make the leap from serial interfaces to the “modern” interfaces found in household equipment. The reason is obvious; serial communication can be designed to use very little power and many USB and Ethernet interfaces commonly operate over ranges that are too short for practical use.

In the case of the AD2CP platform, we chose a path that was conceptually simple at the expense of a more complex implementation. For this reason, the electrical communication can handle either the traditional serial communicating using RS232/RS422, or Ethernet connectivity using four wires at the physical layer (two twisted pairs). Both 10 BASE T and 100BASE-TX are supported.

Having Ethernet in the instrument is attractive for a number of reasons:

- Standard protocols (HTTP, FTP and Telnet)
- Widely used communication standard
- Reliable
- High bandwidth
- Instruments do not have to connect directly to a PC since all instruments can be connected to a network.

Cabled Ethernet was chosen over wireless implementations mainly because:

- It is also suitable for online applications.
- Wireless options can easily be added outside the instrument with a large range of options that can be tailored to the particular application.
- Long cables can be achieved through bridging Ethernet to ADSL or connection to fiber based communication links.
- It significantly reduced the risk of EMI (Electro Magnetic Interference) onto the acoustic electronics since there is no antenna inside the instrument
- Easier configuration

A. *Network processor interface*

Running Ethernet does increase the power consumption, about a 0.75W continuous increase in this implementation. For power critical applications the traditional serial interface was kept since it is very power efficient. Ethernet communication was implemented by using a dedicated network processor. The networking part is powered from a separate power input line which also powers the rest of the electronics. When power is present on this line, the network processor takes over the serial line going to the Doppler processor, which will then no longer receive commands being transmitted over the RS232/RS422 serial interface. For fast data download from the internal recorder, the Doppler processor is halted while the network processor accesses the recorder directly. This enables data download to occur at a very high data rate, ~2.5 Mbytes/s, equivalent to downloading a 1 GByte file in ~6 minutes. If it is not desirable to halt the Doppler processor, data can be streamed over Ethernet continuously while they are simultaneously stored to the internal recorder for backup purposes.

Should power be lost on the Ethernet power input line, a battery connected with a separate connector can serve as a backup power supply to the Doppler processing. Velocity measurements will continue seamlessly and be stored to the internal recorder for later retrieval.

The network processor implementation is mainly standards based TCP/IP networking providing HTTP, Telnet and FTP (File Transfer Protocol) access as well as a DHCP (Dynamic Host Configuration Protocol) option for setting the IP address. There is also a proprietary discovery protocol built in, which uses IP multicasting to retrieve information for all Nortek instruments connected to the local area network (LAN). This protocol also communicates with instruments that are not properly configured for the LAN, something that can then be corrected. It is also useful for retrieving the IP address of the instrument if DHCP is used.

A simple authentication scheme has been implemented to avoid inadvertent communication with the instrument and this is configurable from the WEB page. Firmware upgrade is also available from the WEB page, where firmware for both processors are bundled together in a single file, and upgraded at the same time.

The main purpose of the network processor is of course to add Serial Ethernet Connectivity (SEC) to the Doppler processor as well as enabling recorder file download using FTP. The serial interface of the Doppler processor is accessible over telnet. A dedicated port can be used for ASCII only communication whereas another port provides the complete set of data, including binary data output of the measurements. The telnet interface is very similar to the direct serial interface over RS232/RS422 but some additions are made to simplify the interfacing to the Doppler processor. Most notable is the ability to send a <break> to the Doppler processor just by using Ctrl-C.

B. *Doppler processor*

The main responsibility of the Doppler processor is to process the raw data as it comes in from the A/D converter. However, the Doppler processor is also a central hub for command and control. To facilitate the flow, it operates in several distinct modes. Each mode has explicit commands that control the instrument. The mode concept allows the instrument to conduct multiple simultaneous operations by ensuring that a measurement process will not stop unless explicitly requested with the use of confirmation strings.

A majority of the commands are initiated from the *Command* mode. The main modes for the instrument are:

- *Command* = Command and control
- *Data Retrieval* = Data download from recorder
- *Measurement* = Data collection mode
- *Confirmation* = Confirmation mode

Initializing communication with the instrument is performed by sending a <break>, which consists of three strings with appropriate delays in between. The <break> will either set the instrument in Confirmation mode or restart Command mode. The options for changing mode depend on the present mode of the instrument (see diagram).

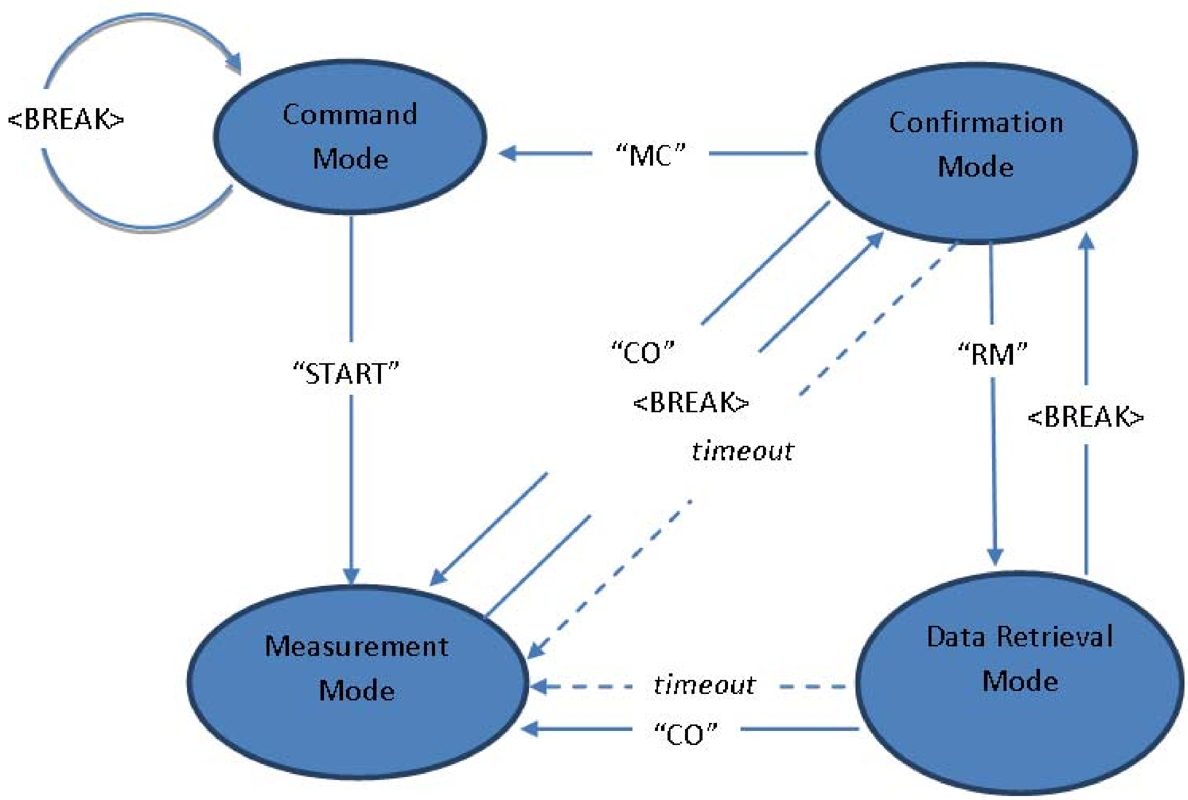
Command interface:

- ASCII based and line oriented (commands terminated with CR/LF)
- Optional encapsulation of commands using NMEA style prefix and checksum to ensure data integrity
- NMEA style commands will return argument names in their response
- Argument limits can be retrieved through commands
- Comprehensive validation and error handling is implemented
- Invalid configurations return the erroneous argument with limits directly, so that each subsequent error can be handled until a valid configuration is achieved
- A single command can be used to retrieve the complete configuration of the instrument with optional output to file
- Commands to set default parameters
- External controllers can use commands to store data in the raw data file (e.g. GPS position)

C. Telemetry files

For online data transmission a versatile scheme for telemetry options is available. This enables external controllers to configure separate handling of all, or a subset, of the measured data. Since the instruments store individual ping data to file, the telemetry option can also be used to average velocity data within the instrument. The telemetry data can either be output directly on the serial line as they are ready, or the data can be stored to a telemetry file for later retrieval. The data format can be selected from a number of formats, including both binary and ASCII data formats. The telemetry file can be read out over the serial interface either in chunks or as a complete file while checksum or CRC on the downloaded data can be applied in a configurable manner. Erasing the telemetry file after data retrieval will ensure that no data is lost if the transfer is interrupted. Since the telemetry file can be retrieved also in data retrieval mode, the instrument will continue measuring after a timeout delay if the data transfer was interrupted.

The telemetry option implemented in the Doppler processor enables system integrators to regularly offload



subsets of the data by using FTP. When the network processor receives an incoming FTP request, it will interrupt the Doppler processor by entering data retrieval mode and mount the file system of the recorder. The data files on the recorder can then be accessed over FTP. The telemetry file can be deleted after it has been downloaded, which is particularly suitable for event driven data downloads.

IV. Current profiling Range

The range of a current profiler is primarily determined by the acoustic frequency, but a host of instrument and environmental parameters strongly influence how far the instrument can accurately measure velocity.

A. Important instrument parameters:

- Transmit power and cell size
- Size and efficiency of transducers
- Receiver noise level

The transmit power and cell size linearly affects the power output and hence the power consumption. Since battery power is limited for self-contained systems, the highest power level and largest cells are normally reserved for applications where power consumption is not a concern. This includes offshore platform mounted or buoy mounted systems where solar power or other sustainable power sources are available. If the transmit power or cell size is doubled, the range for a system operating at 75 kHz increases by 40-60 meters but at the penalty of doubling the power consumption. Larger transducers, like the 25-cm diameter elements used in the Signature75, increase range because the acoustic energy is more tightly focused. The exact improvement in available acoustic power is given by the directivity index, which is proportional to $20\log_{10}(D)$, where D is the transducer diameter. The improvement compared to existing 75 kHz systems is then $20\log_{10}(25/17.5$[1]$)$, which is about 3dB and could be used to add more range or, if desired, reduce the power consumption by a factor of 2.

Transducer efficiency is another important element in the design process. However, it is difficult to describe this quantitatively without going into details about how the transmit and receive circuits are tuned to the electro-mechanical properties of the composite transducers. Suffice it to say that the properties of a composite transducer are generally recognized to provide superior receive sensitivity when compared to a solid disc. In transmit mode the story is different because a significant portion of the active ceramic element is removed and replaced with non-active materials. While beneficial for the overall weight of the transducer, the overall effect on the acoustic power transmitted into water does not represent an improvement over more traditional designs.

The final stage of the system design is to ensure that the receiver noise level is as close as possible to the theoretical level of the receiver design. This is both the most critical and the most complex part of the process because noise sources at these low voltage levels are very hard to track down. The effect on range, however, can be very large and a well-designed and noise-immune current profiler operating in this frequency range can easily get 100-200m more range than a system that is subject to external or internal noise. In the Signature75 we were fortunate to take advantage of a solid understanding of the transducer properties and a long history of fighting noise in a variety of acoustic systems. Noise sources were thus quickly identified and the system is operating with low and steady noise levels that are identical in all three channels.

B. Important environmental parameters:

- Salinity
- Acoustic backscattering cross section per volume

Salinity affects the molecular acoustic losses, which are lower in fresh water than in salt water. As a result, the profiling range is often longer in lakes. Within the ocean, the salinity variations are small and it does not really represent a variable environmental parameter.

The acoustic backscattering cross section varies with the presence of scattering material in the water column. Because the biological activity in the ocean is patchy, the amount and type of material changes with location, depth and time of year. When identifying the variability in scattering material over the profiling range, we compare the actual data with the range variable elements in the sonar equation:

$$EL = SL - 2\alpha R - 20\log_{10}R$$

where α is the frequency dependent water absorption and R is the along-beam range. EL is the receive level and SL is an arbitrary source level.

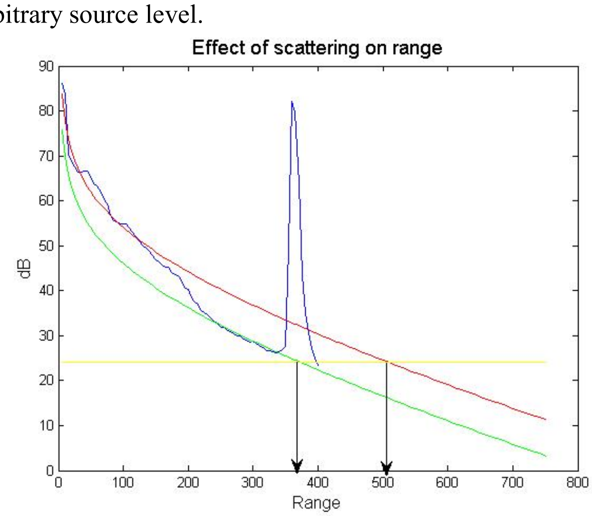


Figure 2 - Scattering from the ocean (blue), decay level fitted to the upper portions of the water column (red) and the lower part of the water column (green).

[1] 17.5 cm is assumed diameter of a 75kHz RDI ADCP

In an experiment in the Oslofjord carried out with a down-looking current profiler operating around 75 kHz, the data (Fig. 2) shows that the scattering in the bottom 100m is about 10dB lower than the scattering level in the upper layer extending from the surface to about 200m. If we assume an arbitrary noise level depicted by the yellow line in the figure, a system deployed only in the upper water column would have a range of about 500m while a system deployed in the lower water column would have a range of about 370 m. Even in a well-designed system this means that unknown scattering conditions have a large effect on the profiling range than any other system variable other than frequency. As a consequence, it is hard to specify the profiling range even to within 100-200m without knowing something about the environmental conditions in advance. Since scattering comes from biological material, and there is usually more biological activity close to the surface, we can generally say that an upward looking current profiler is likely to get more range than a system pointing downward. However, anything beyond this must be based on assumptions about the local conditions.

V. OCEAN TESTING

In June of 2013, a comparative range test was conducted near Toulon, on the south coast of France. Nortek Méditerranée provided all the logistic services including the workboat which took us 2-3nm offshore to an area where the depth exceeds 1000m. For testing purposes, we mounted the Signature75 next to a deep-rated Teledyne RD Instruments 75kHz Workhorse Long Ranger. The mounting frame was designed to allow us to suspend both units over the side of the boat at a depth of about 3m. The systems were left hanging at one depth during the entire experiment while the boat drifted about 1 nm.

Figure 3 - WH 75 kHz to the left, Signature75 to the right

The two instruments would interfere if pinging simultaneously so they were set to ping alternately. Each ensemble consisted of five minutes of single-profile data that were averaged in post processing mode. All conceivable modes were tested, including:

- WH – High power broadband
- WH – Low power narrowband
- WH – Low power broadband
- Signature75 – 75 kHz center frequency, broadband
- Signature75 – 75 kHz center frequency, narrowband
- Signature75 – 62 kHz center frequency, narrowband

The 62 kHz mode in the Signature75 is only available in narrowband mode. It is available because of the extra bandwidth supported by the composite technology used in the transducer design.

A series of different cell sizes were tested but we decided to use 10-m cells for comparison purposes. The definition of broadband is slightly different in the two systems while the definition of narrowband is the same. We also tested the different power levels available in the Signature75, including the “zero-power” mode, which is a receive-only configuration used to detect acoustic and electronic interference. We also tested the Signature75 in non-multiplexing and multiplexing mode, where the former is used when time is of essence and the latter mode transmits sequentially one beam at a time. This mode is included to avoid situations where one acoustic beam interferes with one or more of the other beams because a strong reflector is present in the beam.

The ocean test was quite successful; both systems behaved as expected and a full set of data was collected in four hours. Somewhat to our surprise, the acoustic scattering cross section in the bottom 500m was extremely strong and provided effective profiling ranges far beyond what was expected in the reputedly “clear” Mediterranean waters. As a result, the sixty 10-m cells used with the Signature75 in broadband mode were not sufficient to reach the end of the profile. This led to an immediate upgrade of the firmware to be able to handle up to 200 cells rather than the customary 128, which would not have been sufficient had the system been operating with 5-m cells.

In the end, the test was about profiling range and it has previously been argued that an objective statement about expected range is meaningless without making assumptions about the environmental conditions. More specifically we either have to know or guess the level of biological activity that is assumed to be the source of the observed scattering cross section. The only reference that thus makes sense in a test like this is to compare the observed range with the capability of the WH 75 kHz and how we fare relative to its specified range of 600 m in narrowband, high power mode.

Comparing two system with the same cell size (10m), narrowband, maximum power, and using a 50% drop in correlation as an indicator of the profiling range[2], we can then

[2] The correlation value is derived from the velocity calculation algorithm. A 50% drop is a common number used to indicate when the velocity is unreliable and/or the noise in the velocity estimate has increased by a factor of 2.

say (Fig. 4) that the WH in narrow band mode had a range of approximately 720 meters, the Signature75 operating at 75kHz in broadband mode had an unknown range exceeding 600m (not enough cells) and the Signature75 operating at 62 kHz had a range of about 920 meters.

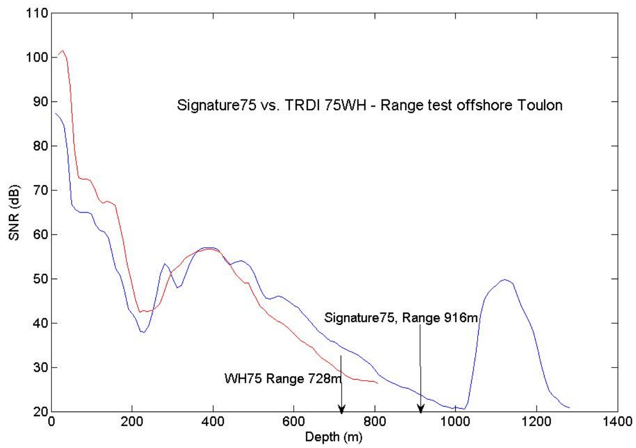


Figure 4 - Comparing the amplitude data from a Signature75 and a WH 75 kHz, both operating with 10m cells and in narrowband mode (about 6% bandwidth)

This last point is not a genuine surprise, when moving from 75 kHz to 62 kHz, the water absorption is reduced and this leads directly to a longer range. However, the main conclusion is clear: The Signature75 in its best performing mode has 200m more range than the WH 75 kHz in its longest-range mode. This may be interpreted as a specified range of 800m when referenced to the specification of the WH 75 kHz (600m) while still bearing in mind the strong scattering variability that exists.

REFERENCES

[1] US Patent 5,208,785, “Broadband acoustic doppler current profile” Inventors Brumley, Blair H, Deines, Kent L. Cabrera; Ramon G., Terray; Eugene A.

[2] Abda, Farès and Schmitt, Philippe, “Single-shot Doppler Velocity Estimation using double chirp pulse compression”, 6th International Symposium on Ultrasonic Doppler Methods for Fluid Mechanics and Fluid Engineering, pp 21-24

[3] Pinkel R. and Smith J. A., “Repeat-Sequence Coding for Improved Precision of Doppler Sonar and Sodar”, Journal of Atmospheric and Oceanic Technology, April 1992, Vol. 9, pp 149-163

[4] B. Brumley, R. Cabrera, K. Deines, and E. Terray, "Performance of a broad-band acoustic Doppler current profiler," IEEE J. Oceanic Eng., vol. 16, pp.402-407, 1991.