ECHOSOUNDER CONCEPTS

TECHNICAL NOTE

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1 KEL 320 ECHOSOUNDER ARCHITECTURE

Figure 1-1 shows the basic structural and functional partitioning of the standard 320M Marine echosounder. It is a simple and modular arrangement designed for the best overall compromise between many competing requirements and priorities. All 320 Series Echosounders use some or all of these modular components depending on the desired configuration.

In the 320M Survey Echosounder, each acoustic channel is provided with its own Signal Processing Module (SPM), which contains the analog front end components, digitizer, and a dedicated DSP. The SPMs perform all signal processing up to and including envelope detection, and send processed and decimated digital envelope data to the Main Processor Module (MPM). Off-loading the computationally intensive signal processing task from the main processor reduces the overall complexity of the system software, while increasing processing power.

Putting the user interface functions onto a separate front panel module is also part of an overall strategy of modularizing the system design. Partitioning the system into easily tested functional blocks reduces maintenance costs and facilitates servicing in the field by board level replacement.

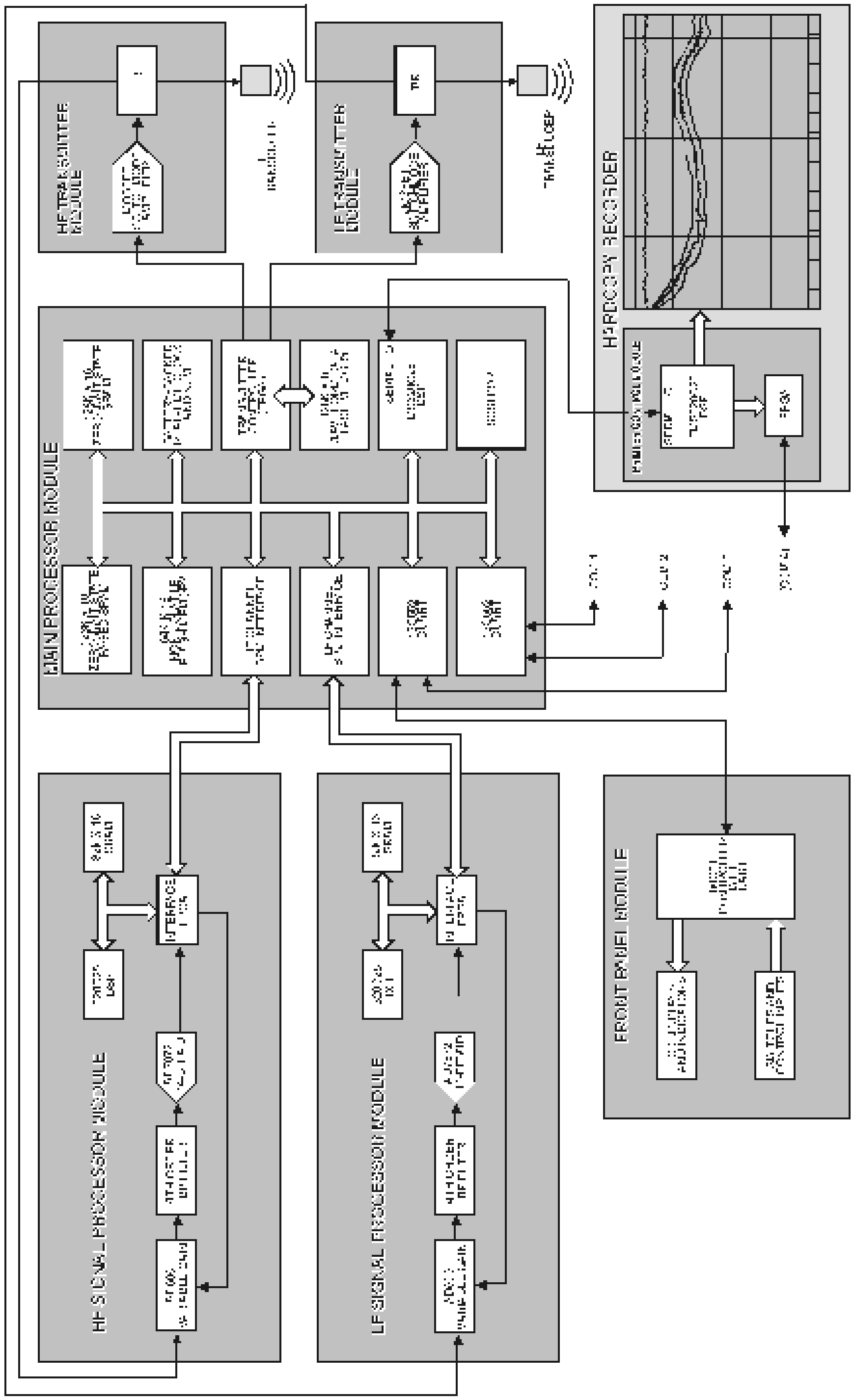
The control panel at the bottom of the unit can be detached as an assembly containing the panel itself, the switches and displays, and the printed circuit Front Panel Module. Removal of the front panel assembly in this manner entails removal of only four screws and four wiring disconnects, and can be accomplished with a Phillips screwdriver.

The thermal hardcopy recorder, which occupies most of the frontal view, is even more modular in execution. The entire printer mechanism, including the printed circuit Printer Control Module, hinges out for access to the paper rolls, and with two wiring disconnects can be lifted entirely off the hinges and removed from the Echosounder as an assembly.

The Transmitter Modules and the Main Processing Module are all mounted to the rear panel of the enclosure with standoffs, and are almost as accessible as the Printer and the Front Panel. The Signal Processing Modules are mounted to the MPM as mezzanine boards. All of these modules are shielded under a protective cover secured with four quarter-turn fasteners.

Finally, the Power Distribution Module mounts directly to a panel which forms part of the external structure of the 320M Echosounder, and which is removable as an assembly with eight screws and several disconnects.

Figure 1-1. The 320M Architecture



2 BASIC ECHOSOUNDER THEORY

2.1 Basic Concepts

The following section is intended for new or occasional operators. It provides a brief introduction to echosounding and to a few of the most important concepts. Experienced users may safely skip this section.

2.2 Pings and Echoes

An echosounder is an acoustic echo ranging device. It measures the depth of the water by transmitting brief pulses of ultrasound downward toward the ocean bottom, and measuring the time it takes for the bottom echo to return. The transmitted pulse, traditionally called a "ping", is a tone of a specified frequency with a duration of anywhere from a sixteenth of a millisecond to four milliseconds. The transducer is mounted through the hull of the ship, near the keel, with its active face pointed straight down. The same transducer is used for both transmitting the ping, and receiving the echo signal. The intensity of the received signal as a function of depth is printed vertically on the graphic recorder. After many repeated pings the bottom is visible as a horizontal black line, which follows the contours of the bottom. The sharpness and clarity of the line depend on the strength and quality of the echo, which depends on many factors, including bottom characteristics, pulse length, depth of the water, and the amount of ambient noise (noise "pollution", which comes from many sources and is unavoidable). The location of the strongest echo is "detected" by software and displayed/recorded as a depth in metres. Each frequency has its own independent display/record.

Echosounder operation is affected by many factors - some much more dominant in their effect than others. Several of the more important factors and their effects are discussed below.

2.3 Bottom Characteristics

The strength of the received echo is strongly affected by the type of bottom. The strongest echoes are produced by rock, gravel or sand (such bottoms are said to exhibit high "target strength"). Mud or silt surfaces have low target strength and produce weaker echoes.

The bottom characteristics can often be deduced from a graphic record, as a result of penetration of the ping into the ocean bottom. Echoes from harder layers a few decimeters beneath the surface of the sea floor often show up as a characteristic layering effect on the graphic record. This is particularly evident in the case of silt overlying rock.

2.4 Pulse Length

The 320 Echosounder's receiver processes the received signal with a bandpass filter with a passband centred at the transducer frequency. This filter allows the received echo to pass through, but rejects ambient noise at all other frequencies. It would seem logical to use the narrowest possible bandwidth, to achieve the greatest possible noise rejection, and thus detect the weakest echoes of the transmit pulse. Unfortunately, it isn't that easy. A signal pulse has a bandwidth approximately equal to the inverse of its duration - thus a one millisecond pulse needs a receive filter with a bandwidth of at least 1 kHz, or it will be attenuated along with the out-of-band noise. The shortest pulses need the widest bandwidth (and achieve poorest noise rejection) while the longest pulses can use the narrowest filters, with the best noise rejection.

On the other hand, the short pulses produce better "range resolution", which permits more accurate depth measurement, and shows more detail on the bottom. Generally, short pulses are used in shallow water, where resolution is important, and where echoes are strong, while long pulses are used in deep water where echoes are weaker, and the noise rejection capability of narrowband filtering is more important.

2.5 Sound Speed

Because the 320 Echosounder is a digital system with a quartz crystal timebase, it does not require internal recalibration due to aging or temperature, and can measure the return time of the echo with a great deal of accuracy. The ultimate accuracy of the depth measurement also depends on the accuracy of the sound speed value used in the computation.

The speed of sound is not a constant, but depends on several factors, most importantly the salinity and the temperature of the water. Normally, the variations in sound speed from location to location are small enough that only occasional adjustments to this parameter are required, such as when transiting from fresh water to salt water. If maximum accuracy is important however, velocity measurements must be made and the sound speed value entered into the echosounder. Since sound speed can vary significantly with depth (as a result of temperature or salinity gradients) it may be necessary to enter an average velocity based on a measured sound velocity profile.

2.6 Draft

Draft is the nautical term used for the depth of the keel (the deepest point) of the vessel below the surface of the water. In echosounders it generally refers to the depth of the transducer below the water surface. The echosounder compensates for the effect of draft, both in the graphic record and in the digital depth display.

The amount of draft varies from time to time as a result of vessel loading, or a transit from fresh water to salt water, and a new value must periodically be entered into the echosounder.

2.7 Bar Check

A "bar check" is a test procedure used to set-up the appropriate speed of sound and draft settings for a sounding session. Typically, a bar check would be performed as follows.

A "bar" (a target which will return a distinct echo)is lowered to a known short distance below the surface. The draft is then adjusted until the depth return from the bar equals the known value. After the draft has been adjusted, the bar is then lowered to a deeper known depth. The sound speed is then adjusted until the depth return from the bar equals the known value. This procedure must be repeated several times until both elements are calibrated. After this procedure, the system will calibrated for the current water conditions and can be left unmodified for the remainder of the sounding session.

3 ACCURACY OF THE KNUDSEN 320 SERIES ECHOSOUNDERS

Note: We are frequently asked to specify the "accuracy" of the 320 series echosounders, and the answer is never straightforward. Although the following discussion does not provide the definitive response, it may shed light on some of the issues.

3.1 Introduction

Although modern echosounders can be sophisticated and complex, the principle on which they operate is simple - transmit a "ping" and listen for the echo. The time it takes for the bottom echo to return is directly proportional to the round trip distance, or twice the water depth. The accuracy of the depth value depends on a great many factors, some intrinsic to the echosounder and some, the local speed of sound for example, which are environmental factors beyond the control of the echosounder designer. This report discusses those factors which are affected by the design and operation of the echosounder.

Sources of error can conveniently be divided into three categories; repeatability, scale and offset. Repeatability is a fundamental limitation - there is no point in calibrating scale and offset to centimetres if the ping-to-ping variability is measured in decimetres. A brief discussion of some of the factors affecting repeatability and some of the design measures taken to enhance this characteristic is provided below.

Deterministic scale and offset errors which are amenable to calibration represent the main focus of this report. Echosounders are traditionally provided with offset and scale adjustments (in the form of draft and sound speed controls) which permit the user to calibrate the unit for his specific transducer installation and local water conditions. The user can set these two parameters by performing a bar check at two different depths (draft is set at the shallow depth, and sound speed at the deeper depth) and iterating the procedure as necessary to refine the values. Alternatively, the user can measure the draft and sound speed directly and enter the values into the echosounder. In this latter case, the user is trusting that the echosounder manufacturer has calibrated the unit correctly (particularly the draft) at the factory. This report discusses the technical aspects of echosounder calibration and accuracy.

3.2 Repeatability

3.2.1 Background

As already mentioned, ping-to-ping repeatability of the measured depth value is a fundamental limitation to echosounder accuracy. It is important to realize that the typical variability in the echo time-of-arrival measurement is much smaller than the total duration of the echo. The problem is not so much to locate the echo but to locate the precise point in the echo, time after time, which represents the calibrated depth value. Repeatability of the depth measurement therefore hinges on repeatability of the echo itself, at the transducer, and also on the repeatability of the process by which the depth determination is made within the echosounder.

3.2.2 Amplitude Effects

The depth determination invariably involves measurement of the precise instant at which the echo amplitude exceeds some threshold. For this to produce repeatable results, the echo amplitude has to be repeatable in relation to the threshold. Obviously echo amplitude varies widely depending on transmitted power, water depth, bottom reflectivity and receiver gain, and so amplitude normalization is a basic requirement of precision echosounding. Traditionally, amplitude normalization has been accomplished with a combination of automatic gain control (when available) and a considerable reliance on operator attention to control settings.

Amplitude normalization in the KEL 320 Echosounders starts with an assessment of the amplitude of each received echo. This is performed in software, after the signal has been digitized, filtered and envelope detected. The details of the algorithm are beyond the scope of this report, but basically it involves increasing the sample frequency of the envelope record by a factor of four with a cubic spline interpolation, and then cross-correlating the upsampled signal with a replica of the leading edge of the expected echo (this is also part of the bottom-picking algorithm). The correlation peak is scaled to produce a very accurate estimate of echo amplitude. Another filter is used with the correlation results to obtain the background noise level. A threshold is then computed as a specified fraction of the echo amplitude (usually 50%). The point in the sample record at which the envelope signal crosses the threshold is computed using polynomial interpolation and floating point arithmetic. The end result of this process is to decouple the depth measurement from both amplitude variations and sample rate limitations.

3.2.3 Bottom Type

Different bottom types can affect not only the amplitude of the return echo but also its shape. A very smooth, flat bottom provides an almost specular reflection with a well defined leading edge and very little off-axis return. A rough bottom, on the other hand, returns a considerable amount of off-axis scattering which tends to elongate the pulse and shift the point of peak amplitude downward. Generally speaking, bottom type effects are more difficult to compensate in the design of the echosounder than the simple amplitude effects mentioned above. The template-matching correlation scheme used in the 320 Echosounders for both bottom picking and amplitude normalization is very effective in minimizing sensitivity to bottom type.

3.2.4 Sample Rate Effects and Truncation Noise

This repeatability issue is peculiar to digital echosounders. It refers to the errors which accumulate whenever a timebase parameter is truncated or rounded off to the nearest sample interval or improperly interpolated. It ultimately places limits on the achievable resolution and therefore the repeatability of the time delay measurement. In early designs it tended to show up in the form of A/D converter sample-rate limitations. In modern echosounder designs it is more likely to be the result of fixed-point arithmetic or poorly written software.

The only practical solution to truncation and round-off noise is to use floating point arithmetic for all timebase related computations, and to use continuous polynomial interpolation when working with time-sampled data. This is the approach taken in all current releases of KEL 320 software. Digital timebase errors are essentially nonexistent in KEL 320 Echosounders.

3.2.5 Pulse Length Effects

If properly implemented, different transmit pulse lengths are matched to different receive filters, with short pulses matched to wide bandwidth filters, and vice versa (there is very little point in transmitting a long pulse unless the receive filter has an appropriately narrow noise bandwidth). The "group delay" of an analog or digital filter is inversely related to the bandwidth and can be quite considerable in a narrowband filter. Fortunately this is a deterministic effect and can be corrected (see the section on offset calibration). A more fundamental repeatability issue arises from the simple observation that long, narrowband pulses have a much longer rise time than short, wideband pulses, and the threshold crossing instant is more sensitive to minor amplitude variations. This is just another way of stating the well-known fact that longer pulses provide poorer range resolution than short pulses.

3.2.6 Frequency Effects

Hydrographic surveyors are well acquainted with the fact that low frequency sound penetrates soft sediments more readily than high frequency signals. They are also aware that the bottoms of oceans, lakes and rivers are often characterized by one or more layers of soft sediments (sometimes very soft, as in "fluff", which may be more liquid than solid) overlying harder, more acoustically opaque materials. Echoes are generated at the interface between substances of low acoustic impedance (such as water) and higher acoustic impedance (sediment). An even greater acoustic impedance difference may exist between buried layers of soft and hard sediment. A low frequency echosounder will often identify a buried layer of hard sediment as the "real" bottom, while a two-channel echosounder will often detect the shallowest interface on the high frequency channel, and a deeper layer on the low frequency.

If the digitized depth values are consistent under these conditions, the results with a two-channel echosounder can provide useful information about the type of bottom. More often, the depth values "bounce" back and forth between one interface and another, producing misleading data.

3.3 Scale Errors

Modern echosounders use extremely precise quartz crystal timebase control, so in theory calibration error in the scale parameter (sound speed) is effectively zero and can safely be disregarded. In practice, the theoretically achievable accuracy can be compromised by errors in the digital processing of timebase parameters, mostly as a result of fixed-point arithmetic or truncation errors. However, this is a software issue, and is easily resolved with good programming practice and floating-point arithmetic as used in the KEL 320 Echosounders.

Note that the scale parameter calibration error referred to here is the accuracy of the correction applied to the depth value by the echosounder to compensate for the speed of sound value entered by the user, either in the course of a bar check or from a sound velocimeter. The depth accuracy still depends ultimately on the accuracy of the sound velocity value provided by the user. In practice, errors in the sound velocity value account for virtually all of the scale effects on the accuracy of the depth measurement.

3.4 Offset Errors

The offset (draft) parameter is calibrated to zero at the factory to account for all of the small time delays built into the signal paths in the echosounder, by far the largest component of which is group delay through digital filters. The group delay through a transversal digital filter depends on the sampling interval and the number of taps, which varies inversely with the filter bandwidth, which is different for each filter. The important point to note here is that this offset calibration must be carried out independently for each of the different receive filters (or for each different pulse length) for each frequency.

This actually represents one of the big advantages of the digital signal filters used in the KEL 320 products, over the multiple analog filters used in other "digital" echosounders. The group delay values of the digital filters are defined precisely in software, and are compensated for in software, once, for all echosounders using that frequency. No "tuning" of pots or coils in individual echosounders is involved, and of course software never drifts.

It should be noted that all of the digital filtering in KEL 320 Echosounders is performed with transversal, or finite impulse response (FIR) filters which are unconditionally stable.

The two-way group delay of the transducer itself contributes a very small amount to this offset error, varying slightly from transducer to transducer, and so the factory offset calibration (zeroing the draft value) is inherently less precise than the scale calibration.

3.5 Factory Calibration Procedures

3.5.1 Introduction

Factory calibration of the offset (or draft) parameter consists of determining the amount of correction required, for each filter, to zero the draft control. These correction values are entered into the software source code and become part of echosounder firmware. The echosounder then applies these corrections when calculating depth values. The correction values are maintained as 32-bit floating point numbers and have units of echogram envelope sample intervals.

The first step in the calibration procedure is to set all of the corrections to zero in source code, and to compile and load this code into an echosounder. A test is then carried out to measure the draft error for each filter. The required correction values are computed from the measured errors, and entered into the source code, which is then re-compiled and loaded into the echosounder. The final step is to carry out tests to confirm the accuracy of the corrections.

Two somewhat different test procedures are used at Knudsen Engineering. Both are briefly described below.

3.5.2 EDI Calibration Procedure

The primary calibration tests are performed with an EDI DSTS-4A Digital Sounder Test Set manufactured by Electronic Devices Inc. This instrument connects to the transducer output of the echosounder and returns a simulated echo signal after an interval corresponding to a depth value which is set by the operator. The echosounder sound speed parameter is set to the value (1500m/s) used by the DSTS-4A, and draft is set to zero. The difference between the depth value preset by the operator (d_1) and the depth value reported by the echosounder (d_2) is then converted to a floating point value in units of sample intervals (the sample frequency of each filter is derived from the sounder's highly stable and accurate 40MHz quartz crystal oscillator):

$$n = (2f_e/1500)(d_2 - d_1)$$

where f_e is the envelope sampling frequency.

This value (n) is then entered into source code as a floating point draft correction for that filter.

3.5.3 Two-point Calibration Procedure

As a check on the accuracy of the EDI instrument, and in cases where the EDI unit is not ideally suited (eg, chirps or very short pulses), an alternative procedure is sometimes used.

The preliminary steps of zeroing the calibration corrections in source code, loading the code into the echosounder, setting sound speed to 1500m/s and draft to zero are carried out as above. The echosounder is then connected to a suitable transducer set up a precisely measured distance from a target. The echosounder is turned on, and depth values are recorded for all filters. The transducer/target separation is then changed to a second carefully measured value, and the test repeated. Given the two carefully measured ranges (r_1 and r_2), and the two depth values reported by the echosounder (d_1 and d_2), the draft correction can be calculated as follows:

$$n = (2f_e/1500)(r_2 d_1 - r_1 d_2)/(r_2 - r_1)$$

where f_e is the envelope sample frequency.

3.6 Summary

To summarize the discussion above:

1) The **scale** error contributed by the echosounder is essentially zero. Scale accuracy is normally controlled by the accuracy of the speed of sound value which is entered by the operator, usually in the course of a bar check.

2) The **offset** error contributed by the echosounder is dependent upon the quality of the factory calibration of each of the filters for zero draft. If present, this error will show up as a change in the depth value when the pulse length is changed, and so its existence and magnitude is easily evaluated. Factory calibrations are carried out under controlled conditions and residual offset or draft errors will invariably be less than the repeatability of the depth measurements.

3) The **repeatability** errors contributed by the echosounder are difficult to measure, because under normal operating conditions they are dominated by instabilities in the propagation medium, which is of course outside the control of the echosounder.

4 DIGITIZED DEPTH VERSUS PRINTED ECHOGRAM

We are often asked about discrepancies between the digital depth value and the printed echogram. Most often, the printed echogram shows the leading edge of the bottom echo to be shallower than the digitized depth. This note addresses the reason for this apparent discrepancy.

In the early days of echosounders, before digitizers, the printed record was the only record. The hydrographer adjusted the draft and sound speed during a bar check using the depths he scaled directly from the printed record, based on his visual determination of the location of the leading edge of the echo. There were two problems with this approach. First, the hydrographer would have noticed that the depth was slightly dependent on receiver gain. By cranking up the gain he could "thicken" the bottom line and decrease the apparent depth slightly. Reducing the gain had the opposite effect. Second, the person who digitized the printed record back in the shop may have had a slightly different view of the precise location of the leading edge of the echo - a bias toward a lighter or darker shade of grey as the threshold point.

Both of these problems result from the fact that the leading edge of the echo is not a distinct event. The echo arrives as an increase in signal strength from the background noise level to the echo peak over a finite period of time. The rise time of the echo has a minimum duration of about half the transmitted pulse length. To put this into perspective, the duration of the leading edge of the echo from a 0.1 ms transmit pulse (a typical pulse length for high frequency shallow water work) is equivalent to almost 4 centimetres of depth. The longer pulses used in deeper water have longer rise times. In practice, however, the echosounder is more accurate than these rise times would lead us to believe.

In the days before digitizers, the easiest way to deal with the rise time problem was to operate the sounder with receive gain increased to the point where the background noise just started to show, and the bottom echo was strongly saturated. This has the effect of setting the detection threshold very low, almost at the noise level, and it works well because the human brain is very good at distinguishing echo from noise. The repeatability (and accuracy) of depths scaled by hand from such records is typically a fraction of the nominal pulse length.

The digitizer software, on the other hand, is designed to set its threshold at the midpoint of the leading edge, at the 50% amplitude point, because this is the value that provides optimum detection performance.

The problem is that hydrographers tend to set their visual threshold at the point in the echogram where the echo first becomes visible, which is often somewhat shallower. The difference between the digitized depth and what the hydrographer sees on the printed record is more pronounced at the high print contrast levels many users prefer, and with longer pulse lengths.

Two points are worth noting. First, the fact that the digitizer threshold is set at the 50% point rather than at some lower (but still visible on the echogram) value does not mean that the echosounder has a built-in error equal to half the rise time of the echo (or a quarter of the pulse length). In fact, the echosounder software is carefully calibrated at the factory to account for this difference. Separate calibrations are performed for each pulse length, and for each frequency. The results of these calibrations, which are equivalent to "zeroing" the draft parameter, are incorporated in the echosounder firmware.

Second, the point at which the echo becomes visible on the echogram is highly dependent on the print contrast mode which is used (see the user manual for an explanation of these modes). With most print contrast modes (particularly including manual contrast), the relationship between the greyscale echogram and the digitized depth is subject to interpretation.

In summary, the digitized depth is most likely correct, even if the printed record appears to be slightly shallower. This should only be a matter for concern if the depth discrepancy is much greater than about a quarter of a pulse length.