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Ultrasonic Inspection of Flooded Mineshafts for Stability Monitoring

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Keywords: Sonar, Ultrasonic, Mining, Shafts, Abandoned, Flooded, Safety

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Introduction

Although coal mine closures in Europe has been very much in the public eye in recent years, the closure of collieries is by no means a recent phenomenon. As a result, countries with a long coal mining heritage have large numbers of abandoned shafts, many of which were sunk in early part of the twentieth century or even earlier. Because of the inherent instability of coal-bearing geological strata, colliery shafts are lined with stone, brick, concrete or steel. However, once the shafts are abandoned and no longer maintained and, unless pumping is maintained the shafts become partially flooded, the linings are liable to decay. This, in turn, can result in partial collapse of the shaft, which can have serious consequences to property and human life. Statistics provide some insight into the size of the problem. For example, in the UK, there are at least 172,000 mine openings (Hughes and Kershaw 2016) and the scope of the problem is similar in other countries.

Many shafts have been closed and partially flooded for several decades with the consequential likelihood that damage to their linings could have already have occurred and that collapse could be imminent. Indeed, UK statistics (Coal Authority 2017) indicated 686 surface hazards related to mining during 2016 and 2017, often involving damage to property, although figures on the proportion relating to shaft collapses is not available. Lecomte et al. (2012) report on the disruptive nature of several such incidents throughout Europe. Accordingly, those organisations with responsibility for ensuring the safety of former mine workings have a requirement for use and development of equipment and techniques for monitoring the linings of these abandoned shafts. CCTV equipment has long been used for the visual inspection of the dry portion of shafts and similar structures (Smythe and Jamieson 1987), and performance has been improved in recent years by the introduction of bright LED lighting, and the use of photogrammetric methods (Wohlfeil et al. 2015). Alternatively, LiDAR (i.e. laser scanning) allows accurate shaft measurements to be made in dry shafts (Salmon et al. 2015; Benecke 2017). However, mine water is often polluted with mineral particles in suspension which very much reduces the penetration of light and, in addition, causes light to be scattered. Under these conditions, optical methods, including even LiDAR equipment with a blue/green laser which is intended for underwater use, perform not nearly as well as in dry shafts, and often they are almost entirely ineffective (Herrero et al. 2012).

The research and developments reported here was carried out to provide a means of inspecting flooded mineshafts and thereby provide a solution when optical methods are unsuitable. In particular, building on an initial feasibility study reported by Herrero et al. (2012), two so-called periodic inspection modules have been developed using ultrasonic techniques, otherwise known as sonar, to provide visibility through potentially turbid water. The main purpose of these modules is to allow shafts to be inspected periodically, with a view to detecting changes since a previous inspection was carried out, because this change detection could be indicative of damage to the lining, a possible precursor to collapse.

Ultrasonic Inspection

Ultrasonic inspection makes use of high frequency compression waves which can propagate through water – even turbid water – and are reflected by solid surfaces. By transmitting ultrasonic pulses and measuring the time taken for a reflected signal to be returned, the distance to solid objects can be calculated. The strength of the signal can also be used to provide information about the density of the target, thereby allowing different materials to be differentiated. Traditionally, the equipment is able to rotate the sonar beam to scan a target and, as a result, build up a two dimensional model or image. As an alternative to mechanically scanning, multi-beam sonars, which use electronic beam steering, provide the benefits of no moving parts and a much higher speed of operation (Morse 2015) but at a much higher cost.

Sonar equipment is used, primarily, for marine applications such as inspecting sub-sea pipelines or the substructure of constructions including oil platforms, wind turbines, bridges and quays (Clubley 2015; Thompson et al. 2005). Sonars are traditionally categorised as profiling and imaging and it is important to recognise the difference between the two.

A profiling sonar (Atherton 2011a) generates a narrow conical beam, commonly about one degree in diameter, which is scanned perpendicular to the target. Figure 1 shows a typical profiling sonar, illustrating how it would be used in a seabed application such as inspecting a pipeline, when the beam intersects the target a right angles. The sonar is usually programmed to record a single return signal from each pulse, this being either the first or the strongest signal, although multiple returns could be recorded, usually within a short timing window. As the name suggests, the result is a profile of the target, as also illustrated in Figure 1. Such a profile allows accurate measurements to be made. The forward movement of the sonar at right angles to the direction of scanning – achieved, for example, by mounting it on an Underwater Autonomous Vehicle (UAV) – allows a series of profiles to be obtained.

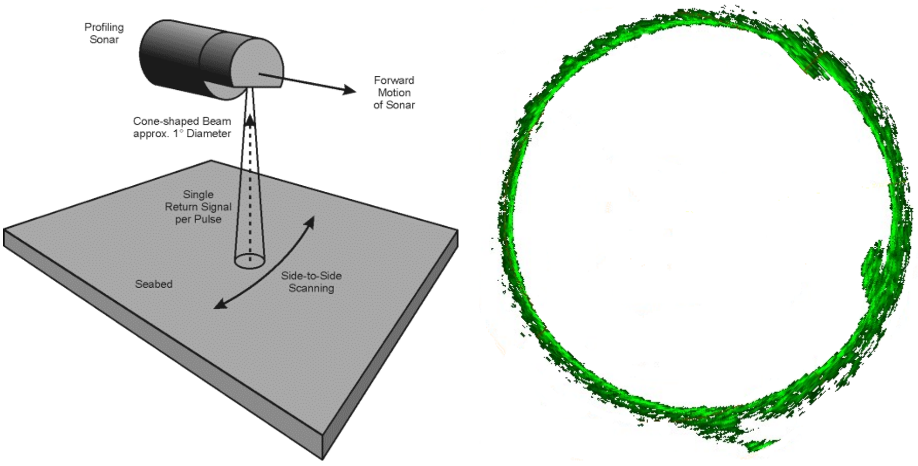

Figure 1. The principle of operation of a profiling sonar is shown at the left; typical results in the form of a preliminary profiling mine shaft survey, are shown at the right.

An imaging sonar (Atherton 2011b) generates a fan-shaped beam which is commonly about one degree in one dimension by 30 degrees in the other dimension. Figure 2 shows a typical imaging sonar, illustrating how it would be used in a seabed application when the beam intersects the target obliquely. The sonar records a large number of return signals which are differentiated by timing and, therefore, the distance to the target. Because different materials produce different strength signals, this allows a greyscale or false colour image of the target to the built up, in an analogy to a visual image, as also illustrated in Figure 2. The forward movement of the sonar at right angles to the direction of scanning allows a large area of the seabed to be imaged.

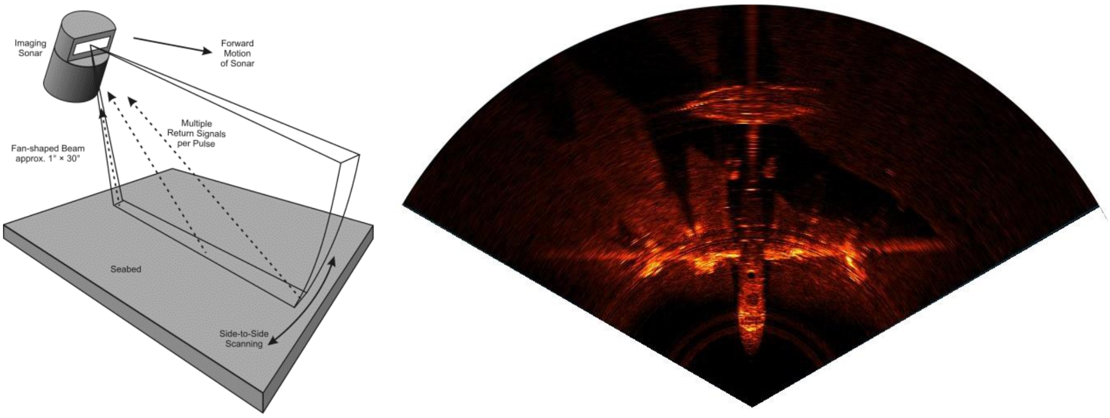

Figure 2. The principle of operation of an imaging sonar is shown at the left; typical result in the form of a seabed survey showing a crashed aircraft, produced using a Tritech Gemini multi-beam sonar, are shown at the right.

Ultrasonic Shaft Inspection Requirements

The primary requirement of sonar for inspecting the lining of abandoned flooded shafts is to acquire geometrical data which has sufficient resolution to detect damage at an early stage, and is sufficiently repeatable to allow comparisons to be made between one inspection and another carried out some time later. In the following discussion it is assumed that the sonar is mounted so that it scans the shaft through 360 degrees horizontally, and the unit is winched into the shaft while scanning so that scans can be obtained throughout the depth of the shaft.

The resolution achievable depends on three parameters: the footprint dimensions of the sonar beam, the horizontal angular step size, and the vertical distance between successive scans. Today’s profiling sonars have a typical beam width of one degree which gives a footprint approximately 120 mm in diameter at the maximum expected range of 7 m. This is considered adequate to detect fairly minor damage, especially since features smaller than the footprint can be detected, even though multiple features smaller than the footprint cannot be differentiated. The figure for the maximum range assumes the largest shafts are 8 m in diameter and, as a worst case scenario, have an off-centre access, 1 m from one wall. The majority of shafts are smaller in diameter, thereby providing better resolution. Most sonars have various angular scanning step size options which allow the user to offset angular resolution against the scanning time. Steps of less than the beam width are generally available, thereby allowing a degree of overlap between successive measurements. The vertical distance between scans depends on the speed at which the sonar is winched into the shaft. This is under the control of the user and, again, represents a choice between resolution and scanning time.

Although the above analysis suggests that commonly available profiling sonars are suitable for detecting damage to shafts linings at an early stage, it is recognised that there are some potential drawbacks to using only a profiling sonar. First, an inspection exercise will be very time-consuming. The time depends on the horizontal angular step size and the distance from the sonar to the target (related to the shaft diameter), both of which affect the time to acquire a 360 degree scan, plus the winching speed. Taking the Tritech Super SeaKing Profiler as an example, this being the sonar used in the UIM (one of the periodic inspection modules that are described here), with the sonar in the cross-sectional centre of an 8m shaft and a 0.9 degree step size, the time per 360 degree scan would be approximately four seconds. If it is necessary to be able to detect objects with a vertical dimension equivalent to the height of a course of bricks (typically 75mm including the mortar), the maximum winching speed would be 75mm per 4 seconds or approximately one metre per minute. Surveying a shaft with 500m flooded section would, therefore, would take eight hours, excluding setup and dismantling time.

Second, although detailed analysis of the data will be carried out as a separate exercise, after the data has been acquired, it would be beneficial if the operator is able to identify features in real time as the data is being collected. This would allow the operator to make a judgement on whether a particular feature is significant and, if so, this might result in further data being collected at a higher resolution. However, identifying features in a shaft from a profile is difficult and error prone.

It might be assumed that the use of an imaging sonar would resolve both these issues so a combination of a profiling and imaging sonar would offer an ideal solution. In particular, because it captures large swathes of the target at once, the imaging sonar would allow the shaft to be inspected quickly. Although it would not provide accurate dimensional information, it would allow areas of potential interest to be identified so that the area can then be surveyed in detail with the profiling sonar. Then, when the shaft is inspected using the profiling sonar, the continuing use of the imaging sensor would assist the operator in identifying the features being measured by the profiling sonar.

An initial analysis suggested that the benefit of adding an imaging capability might not be as great as this superficial view suggests. Unlike the case of using an imaging sonar to survey a seabed, where objects of interest will normally protrude above the seabed, in surveying mineshafts, features of interest will normally take the form of holes in the lining. For this reason, the usual arrangement of scanning at an oblique angle would not be ideal and, instead, better results would be obtained by scanning perpendicular to the shaft wall. However, in this configuration, the usual relationship between the time a return signal is received and the location of the target does not apply. Instead, signals reflected from points equidistant above and below the sonar would be received at the same time with the result that a confusing image would be obtained. The image would be further confused in the highly reverberant environment of a mine shaft because non-direct signals, i.e. signals that have been reflected more than once, will be detected. It should be noted that a profiling sonar can also suffer from multi-path signals, but this is less of a problem because, unlike the case with an imaging sonar, return signals are only recorded during a small timing window, the threshold being user selectable.

Despite these potential drawbacks, it is clear that an imaging sonar will allow the shaft to be surveyed more quickly than with a profiling sonar. Although the acquired image will not be analogous to a visual image, it was anticipated that the exercise will identify areas with notably different characteristics to other parts of the shaft and, with experience, operators will be able to identify areas where it would be beneficial to carry out a more detailed scanning exercise with the profiling sonar. Although the use of an imaging sonar does not necessarily fulfil the aim of allowing the operator unambiguously to identify features visually, this functionality could be provided by using software to stack the results of successive profile scans to produce a pseudo-3D image of the type commonly referred to as a waterfall display. This functionality has been provided in the software written to support the UIM.

Supplementary Shaft Inspection Requirements

In addition to the basic sonar requirements, the safe and effective operation of a periodic inspection module requires some additional functionality. Here these requirements are discussed, but attention will not be given to functionality that can be thought of as transparent, in the sense that it is essential to the operation of the equipment but does not provide primary functionality to the user. In this category are the power supplies and data communication interfaces.

The first such supplementary requirement is to provide information on, or carefully control of, the modules’ position and orientation within the shaft. The depth of the module in the shaft is measured primarily using a cable counter on the winch. However, without careful attention, a periodic inspection module winched into a shaft will exhibit unintentional movement within the shaft’s cross-section due, mostly, to rotation around the cable’s vertical axis and pendulum motion. Because any such movement would seriously jeopardise the accuracy of the sonar data, and make comparisons between different surveys almost impossible, hardware is required either to detect such motion so that the software that analyses the data can compensate for it, or to prevent it. Different approaches have been adopted in the two periodic inspection modules as described later.

The second supplementary requirement is a means of detecting obstacles in the shaft, immediately below the periodic inspection modules, which could pose a collision risk. It is recognised that, although the purpose of the periodic inspection modules is to survey the flooded section of the shaft, it is necessary to winch the equipment through the dry portion of the shaft first. Techniques applicable to obstacle detection above and below the water might be needed, therefore, yet economical and effective solutions which will operate in both these environments are not available. Accordingly, two forms of obstacle detection have been used – one for use in the dry portion of the shaft and one for use in the flooded section. An appraisal of available techniques suggested the use of a downwards-pointing CCTV camera for use in the air and a downward pointing sonar altimeter for use underwater. A sonar altimeter operates in a similar way to the profiling and imaging sonars already discussed but does not scan the beam. As such, it provides a single reading of the distance to the closest reflective object in its field of view. It should be noted that, because of the explosion risk in a potentially explosive atmosphere, the use of CCTV above the water level may not be permitted in some countries while, in others, it is permitted only following atmospheric testing. For this reason, the use of CCTV above the water level is not available on one of the periodic inspection modules developed.

Periodic Inspection Modules Developed

Two different periodic inspection modules have been developed. This approach has provided instruments that are suitable for end users with different requirements, and it has also permitted different technologies to be researched. The two instruments, referred to as the Ultrasonic Inspection Module (UIM) and the Multifunctional Monitoring Module (MMM), are described in the following sections. Here the functionality of the two modules is outlined and the results of initial tests are provided. It should be noted that, although in normal use, the purpose of making measurements with the periodic inspection modules is to detect changes since the previous inspection, probably a few years earlier, the timescale of this project did not permit comparisons to be made. Instead, single inspections have been carried out in a number of shafts to confirm that the modules are capable of achieving the necessary performance.

Ultrasonic Inspection Module

The Ultrasonic Inspection Module (UIM) – see Figure 3 – is designed as a very cost-effective unit for use by end users with a requirement for a basic shaft geometry monitoring capability who either do not have the budget for the more fully-featured MMM or do not require the additional capabilities it offers. It also has a much smaller diameter than the MMM – 300mm compared to 540 mm to 1960 mm in diameter at the largest point, depending on the configuration – so this will allow its use in shafts with a small access port as is common, for example, in many of the capped shafts in the UK.

Figure 3. The Ultrasonic Inspection Module (UIM) comprises the Cable Interface Sub-module (CIS) which contains the power supplies and communications at the top, the Geo-referencing Sub-module (GRS) containing inertial measurement units in the middle, and the Profiling and Collision Avoidance Sub-module (PCAS) which contains the profiling sonar, CCTV camera and sonar altimeter, at the bottom.

The UIM provides a single capability, that of obtaining sonar profiles in the flooded section of a shaft. This is achieved using a Tritech Super Seaking Profiler. It does not offer an imaging sonar capability although the associated software can generate a waterfall display in real time to assist the operator in identifying features – see Figure 4.

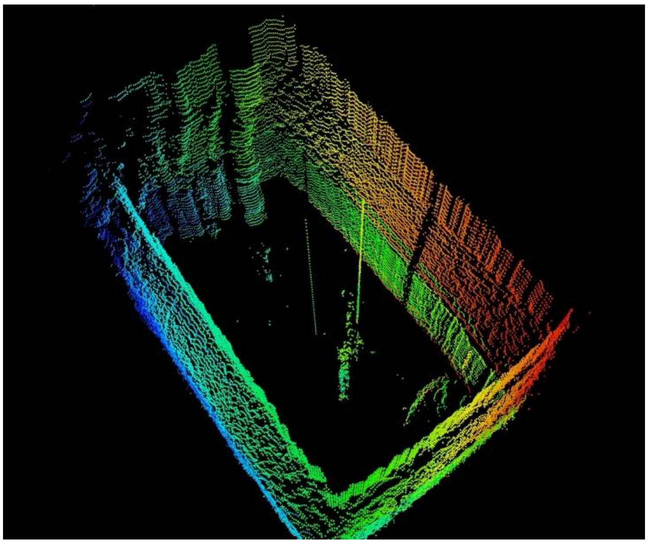

Figure 4. Waterfall display generated by UIM in test tank.

The UIM contains a geo-referencing capability. This allows unintentional horizontal movement, such as rotation and pendulum motion, to be recorded so it can be taken account of by the software which records, displays and analyses the profiles. The hardware also provides data to improve the accuracy of the depth measurement as obtained from the cable counter on the winch without the need for on-site calibration. This uses a custom-designed fibre-optic survey-grade gyrocompass and an inertial measurement unit. Using three orthogonal gyroscopes and three orthogonal accelerometers, true-heading, roll, pitch and angular increment, and velocity increments, with respect to the X, Y and Z axes, are monitored.

Obstacle detection is provided by a downwards-pointing CCTV camera with integral LED illumination for use above the water level and a sonar altimeter below the water level.

A test took place in a shaft at the abandoned Thorpe Hesley Colliery in South Yorkshire, UK – see Figure 5. This exercise served to confirm the ergonomics, mechanical stability, obstacle detection, and waterproofing of the UIM, especially in an environment which was characterised by a small opening in the concrete cap, which is typical of many abandoned shafts in the UK. Further field tests to prove the operation of the profiling sonar were not possible because access restrictions prevented further work in this and other shafts. However, this was not considered problematic because work in a test tank had already proven the operation of the profiling sonar (see Figure 4), and extensive tests of the MMM, which are described later, provided adequate evidence of the suitability of a profiling sonar for the inspection of abandoned shafts.

Figure 5. UIM field trials at Thorpe Hesley, UK.

Multifunctional Monitoring Module

The Multifunctional Monitoring Module (MMM) – see Figure 6 – is designed as a fully functional module for use by those end users who require the additional features it offers, can justify the cost of the more expensive unit, and intend to use it in shafts that have a sufficiently large access port. The MMM features arms, on which the CCTV cameras are mounted, that can be configured vertically or horizontally, depending on the size of the shaft’s access port.

Figure 6. The Multifunctional Monitoring Module (MMM), with the arms shown in their vertical position.

As the name suggests, the MMM is designed to provide a broad range of shaft monitoring capabilities. Here only the ultrasonic capabilities are discussed in detail although, for completion, the other features are listed. These features include a range of CCTV cameras with LED lighting, which can be configured to point in any direction. Although not present on the current prototype, provision has been made to include water sensors to provide information on the chemical composition of the water, and a means of returning samples to the surface for more detailed analysis. In addition, future thermal sensors will be able monitor water temperature to provide information on inflows.

Ultrasonic monitoring is provided by a Kongsberg Mesotech 1171 Series sonar, part number 975-23850000, which includes both a profiling and imaging sonar capability in the same package, which can be used simultaneously. The imaging sonar capability provides extra functionality for the end user, even though, as already discussed, the exact nature of this was not entirely clear before the first tests were carried out. In addition, the use of an imaging sonar allowed research to be carried out into the performance of this technology in an environment which has many differences to its more common environment of a seabed.

Because the MMM is larger in diameter than the UIM (even with the arms configured in the vertical position) and is, therefore, only suitable for use in shafts with larger access openings in their caps, a different method of handling unintentional horizontal motion was considered feasible and has therefore been adopted. The method provides a reduction in the cost of the hardware, compared to the approach used in the UIM, but at the expense of an increase in the setup time at the shaft. The MMM does not include a geo-referencing facility so it is not able to monitor any unintentional rotational and pendulum motion in the shaft. Instead, it uses a passive stabilisation technique to minimise any such movement. Before winching the MMM into the shaft, a supplementary weighted module is winched into the shaft to provide a stable guide wire. The MMM is then connected to the guide wire via a rigid horizontal linkage which is able to slide down the guide wire as the MMM is lowered into the shaft, with very limited scope for rotation or pendulum motion.

Underwater obstacle detection is provided by a sonar altimeter although no obstacle detection is provided above the water level. This is in consideration of the regulations in Poland, the region for which this module was primarily designed, which do not permit non-ATEX cameras to be used in the dry portion of abandoned shafts.

Field trials of the Multifunctional Monitoring Module have been carried out in five locations in Poland, two of which can be seen in Figure 7. Cooperation with two polish mining related companies allowed the prototype to be tested in conditions which would be typical of genuine application of the MMM. The individual shafts differed in their lining, diameter, access, size of the shaft opening, installed equipment, and the organisation of the site, thereby providing proof of the MMM in a wide range of different conditions.

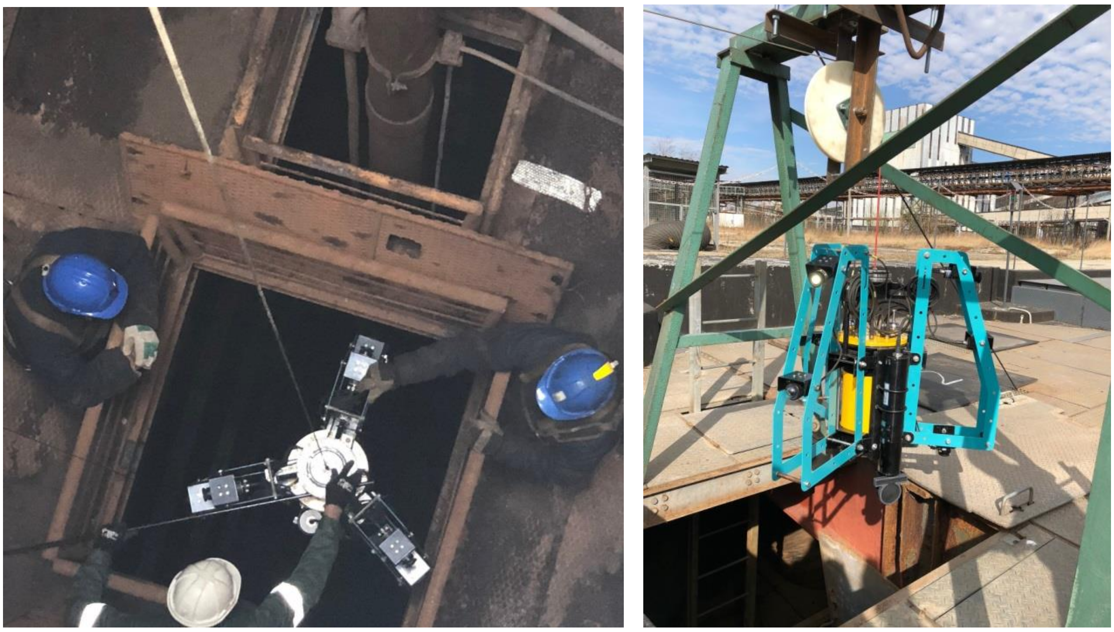

Figure 7. MMM field trials at two mine shafts in Poland. The arms are configured horizontally on the left and vertically on the right.

The most crucial instrument in the MMM, due to the poor visual conditions in the underwater part of shafts, is the scanning sonar. Therefore, considerable time was taken in setting its parameters and adapting it to shaft conditions, which are undeniably different from the more common environment of a seabed. The Kongsberg Mesotech 1171 Series sonar in the MMM includes both a profiling and imaging sonar capability. Although profiling sonars are suitable for detecting damage to the shaft (for example in the UIM), the addition of the imaging capability was shown to provide benefits to the functionality of the module. First, it can be used to quickly localise specific regions of the shaft where deformations are likely to have occurred, such as an intersection with horizontal galleries. In addition, the imaging sonar capability supports the profiling scanning while the two are being used simultaneously. It was shown that the availability of imaging data assists the operator in setting the threshold of the profiling sonar to reject multipath signals – this is discussed by Atherton (2011a), albeit not specifically in a mineshaft environment. Therefore, by inspecting both the profiling and the imaging output, the reliability of the data is improved. Sample output from one of the field tests is shown in Figure 8.

It is pertinent to point out that the accuracy and resolution of the output could not be confirmed because, prior to the development of the MMM, reliable underwater shaft surveys could not be carried out, so no up-to-date data was available for comparison purposes. However, it is important to point out that the sonar manufacturer’s quoted accuracy and resolution are well within that required to detect defects in the lining as small as a single missing brick. However, some aspects of the resolution are dependent on decisions made by the operator as already discussed.

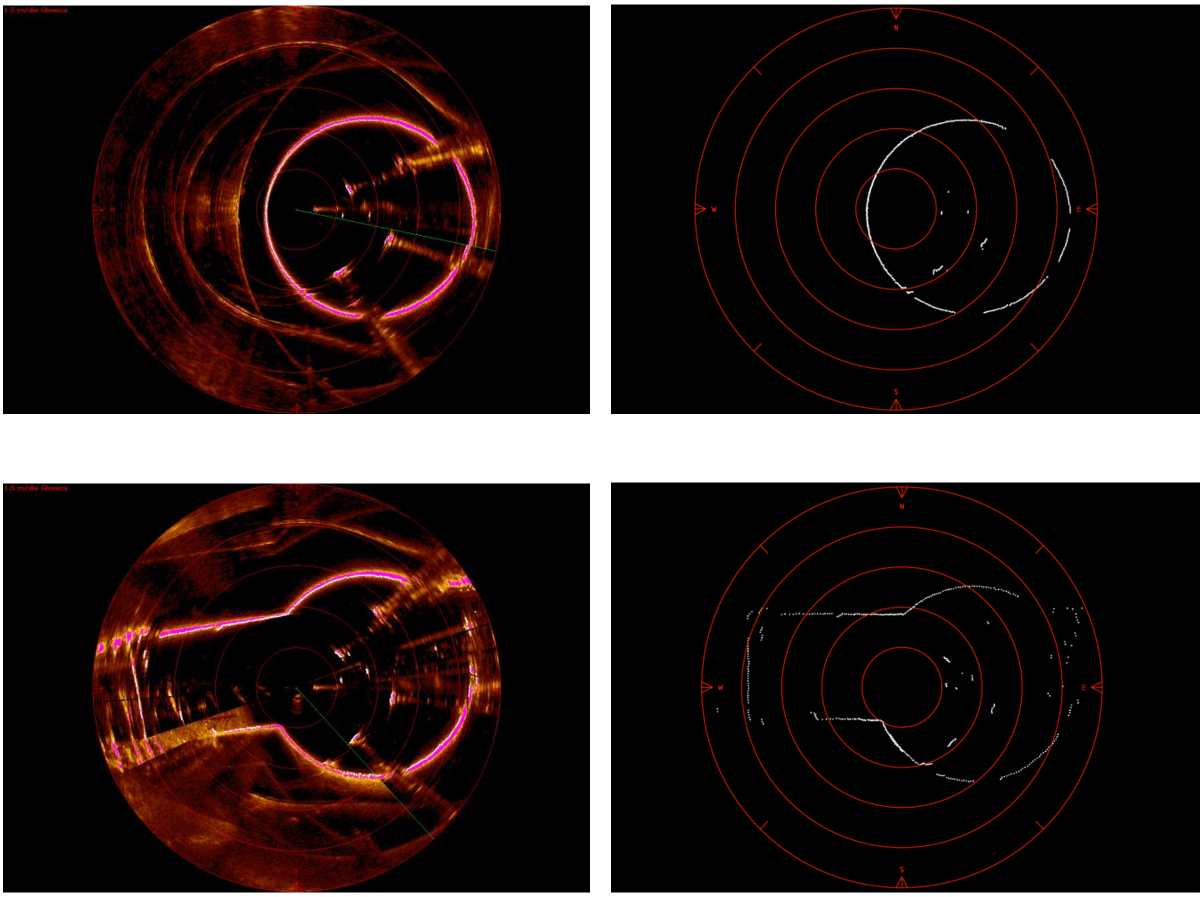

Figure 8. Sample MMM output. The top row shows a section of the shaft with few features, except for several vertical pipes, and the bottom row shows a section of the shaft containing

intersections with a horizontal gallery at both sides of the shaft. In each case, the left image shows a combined profiling and imaging display, and the right image shows profiling data only. The red circles represent the scale which is 1.5 metres between circles.

Conclusion

Periodic inspection modules have been developed to permit those organisations with responsibility for the safety of abandoned mine shafts to survey the flooded sections of these shafts for signs of damage to the lining. Such a facility will augment existing equipment and techniques that are used for the less demanding process of surveying the dry portions of abandoned shafts. The two modules provide different monitoring capabilities, depending on the requirements and budget of the user organisation, but both incorporate a profiling sonar which allows accurate geometric measurements of the shaft's cross-section to be captured. This capability will allow changes to the lining since a previous surveying exercise to be detected. Since such a change could be indicative of damage to the lining, a possible precursor to collapse, it will make a major contribution to ensuring shaft stability with consequential benefits to property and human life. The addition of an imaging sonar capability on the MMM has reaped benefits, despite some initial doubts over its suitability in the non-typical mine shaft environment. In particular, it allows the operator to more rapidly identify areas of potential interest, and it also assists the operator in correctly setting the threshold of the profiling sonar to reject multipath signals.

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Mining Technology (TIMM A)

Response to Reviewer Comments

I'd like to thank the Editor and Reviewers for their dedicated work in reviewing our paper "Ultrasonic Inspection of Flooded Mineshafts for Stability Monitoring". Obviously we are very pleased that it was found to be of interest and suitable for publishing in Mining Technology (TIMM A). We trust that its publication will benefit those who are responsible for the legacy of former mining operations and, in so doing, will have a positive effect on safety.

We were asked to address two issues. These are listed below, in normal text, followed by our response in indented italics.

A couple of the images in Fig 8 are of low quality – please improve the quality to publication standards.

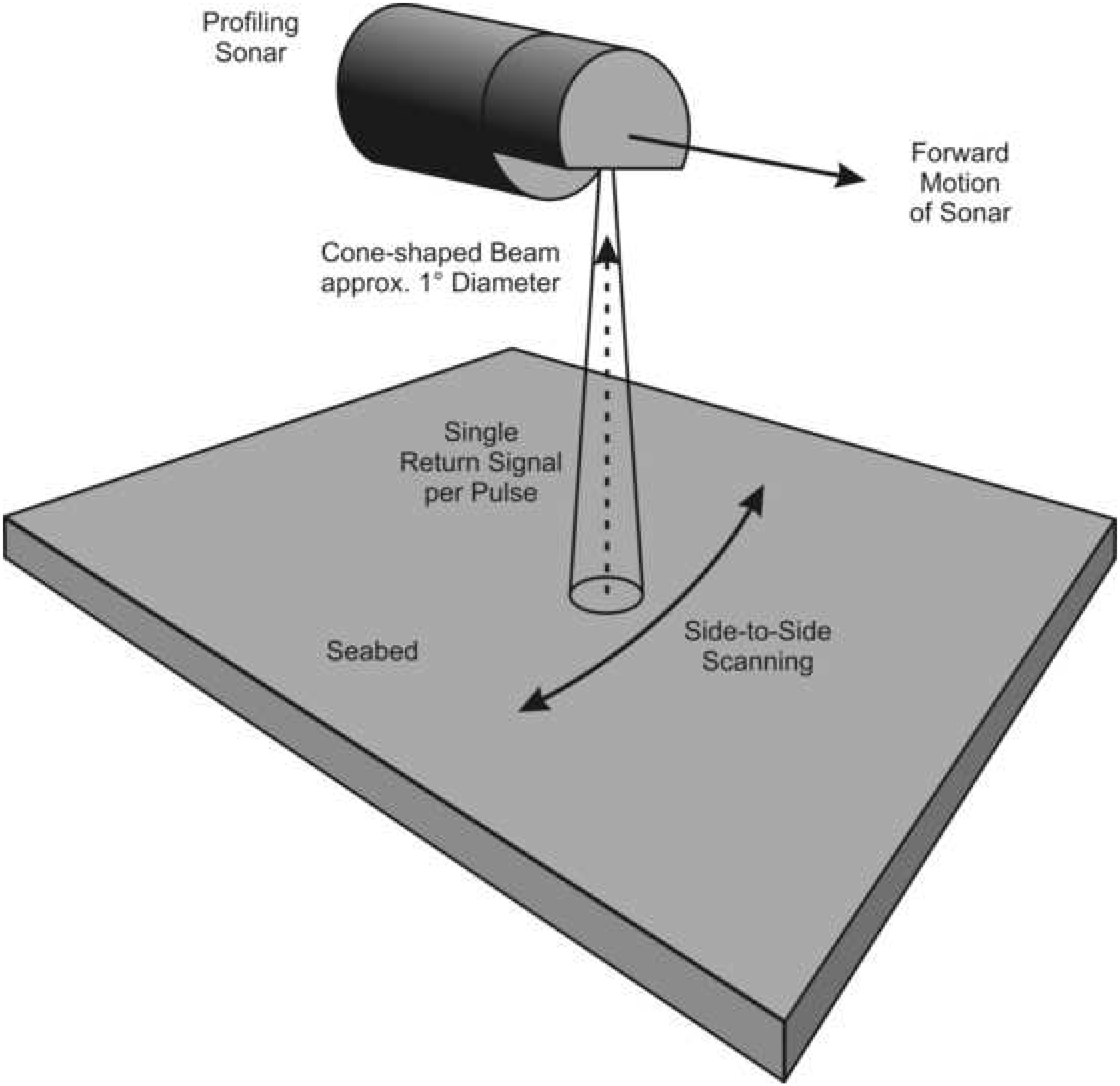
> *I agree that the two right-hand images in Fig 8 were faint and difficult to read. Originally I had edited the images produced by the sonar software to have the white background, as shown in the original paper, but I think this was a mistake and that the black background would be better. I checked this with Peter Dowd on 8th April, who agreed that the original versions with the black background would be acceptable. However, I also managed to make the red and white parts of the images bolder. These new images have now been provided.*

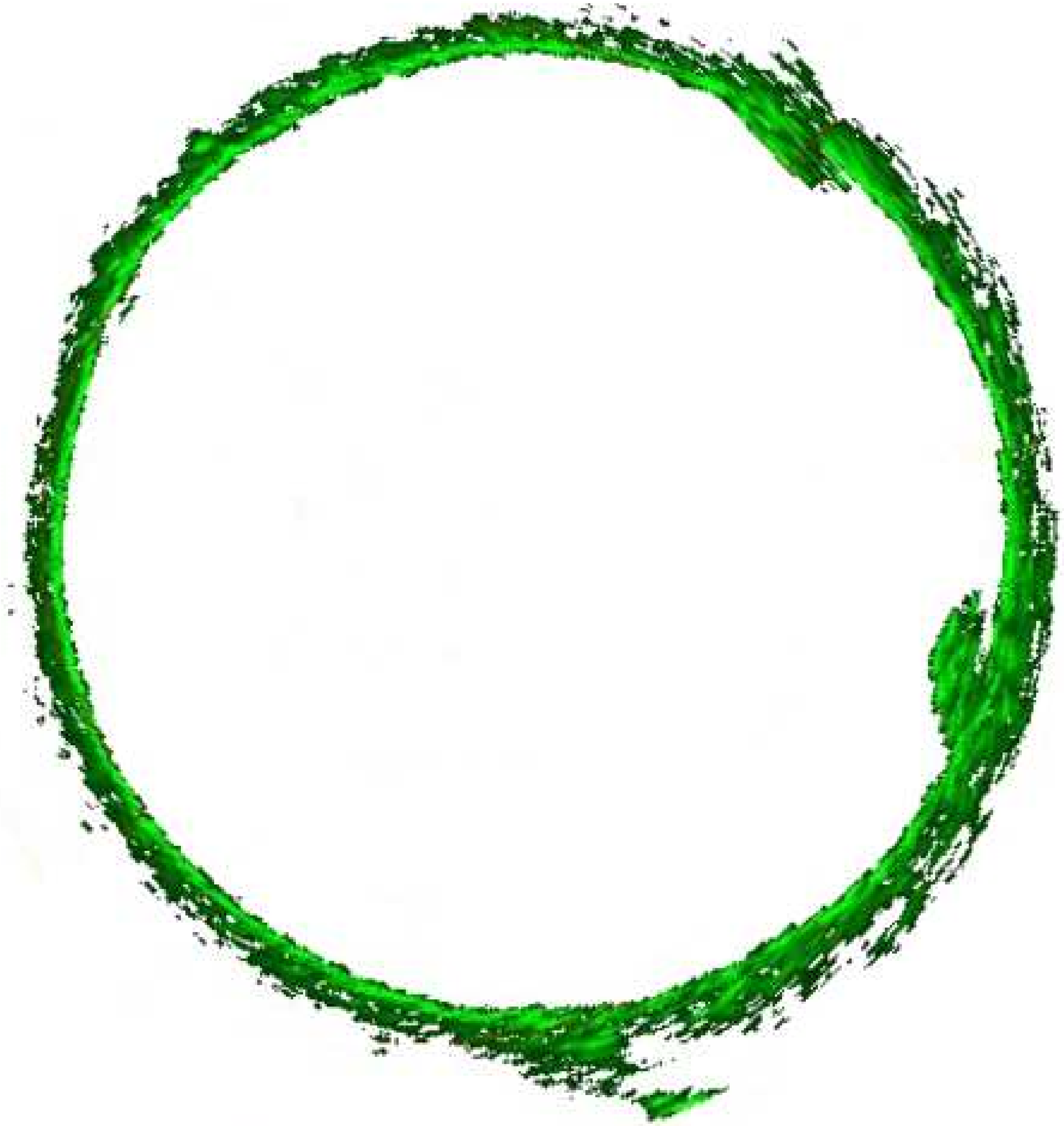
Also not sure what 1.5/div means (which div?)

> *The 1.5m/div relates to the distance between the red circles on each of the images. This has been explained in the caption to Fig 8.*

Regards,

Mike Bedford


Profiling
Sonar
Forward
Motion
of Sonar
Cone-shaped Beam
approx. 1° Diameter
Single
Return Signal
per Pulse
Side-to-Side
Scanning
Seabed



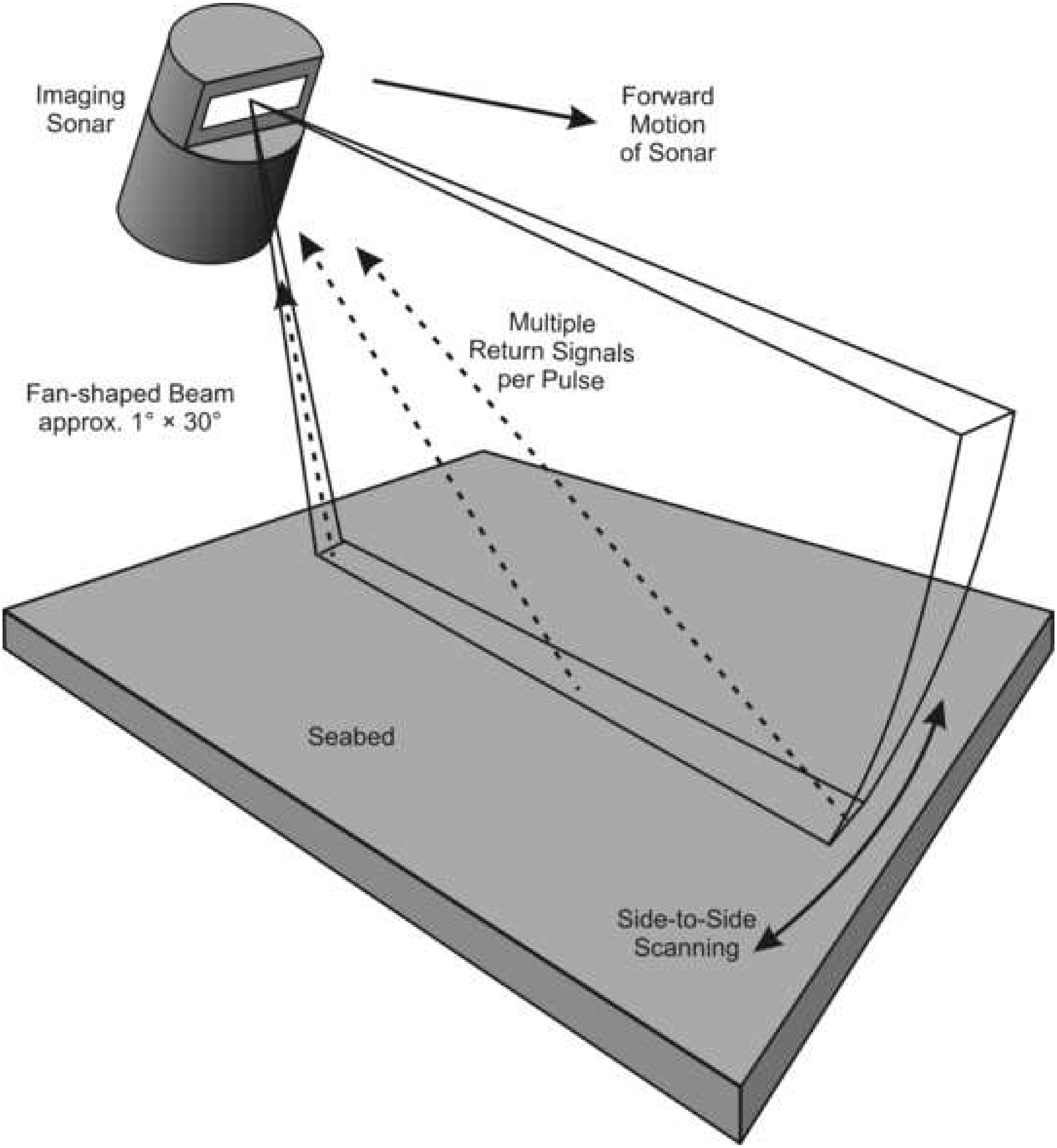

Imaging
Sonar
Forward
Motion
of Sonar
Multiple
Return Signals
per Pulse
Fan-shaped Beam
approx. 1° × 30°
Seabed
Side-to-Side
Scanning

Figure 2 Right

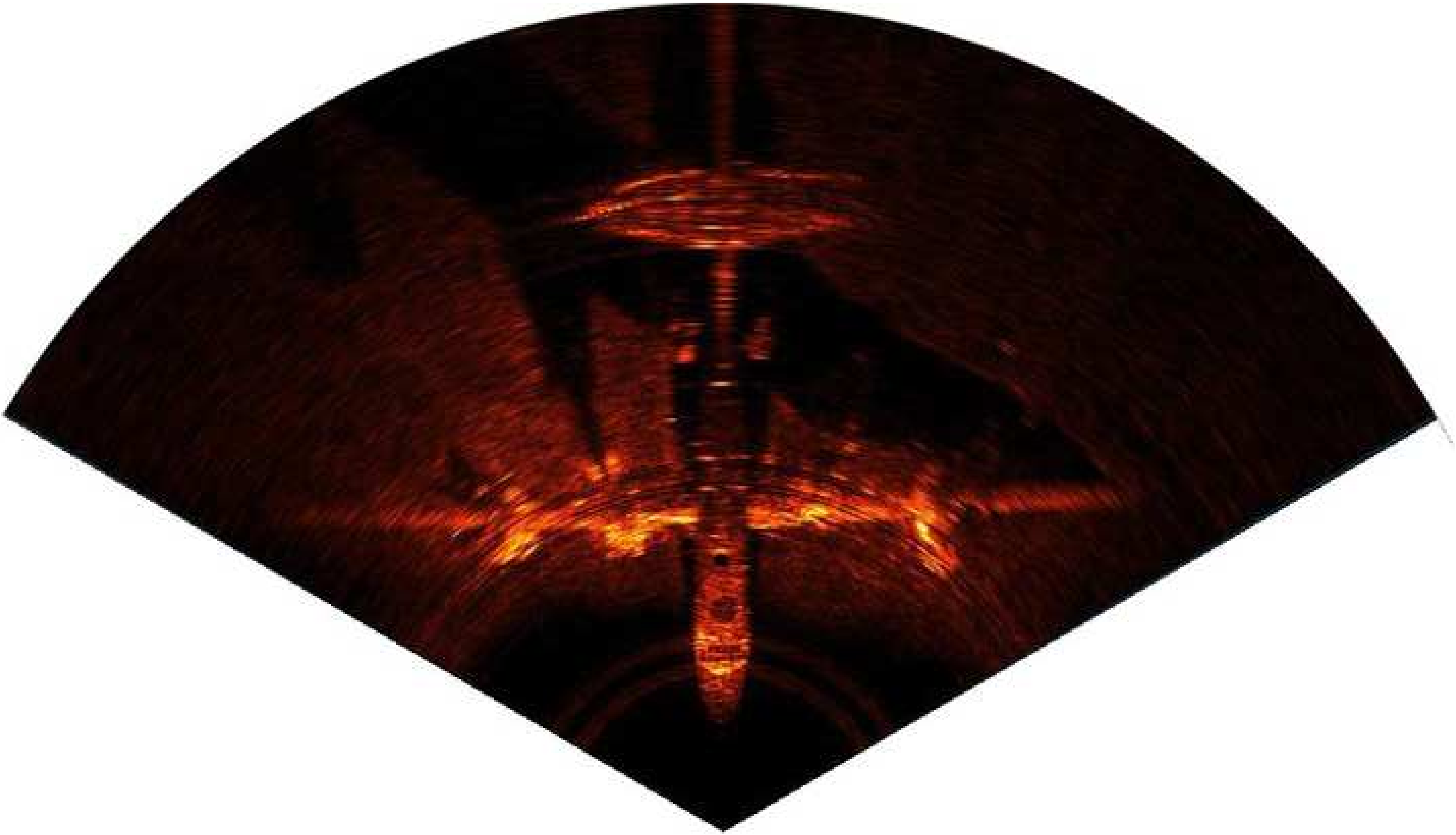


Figure 3

Figure 4

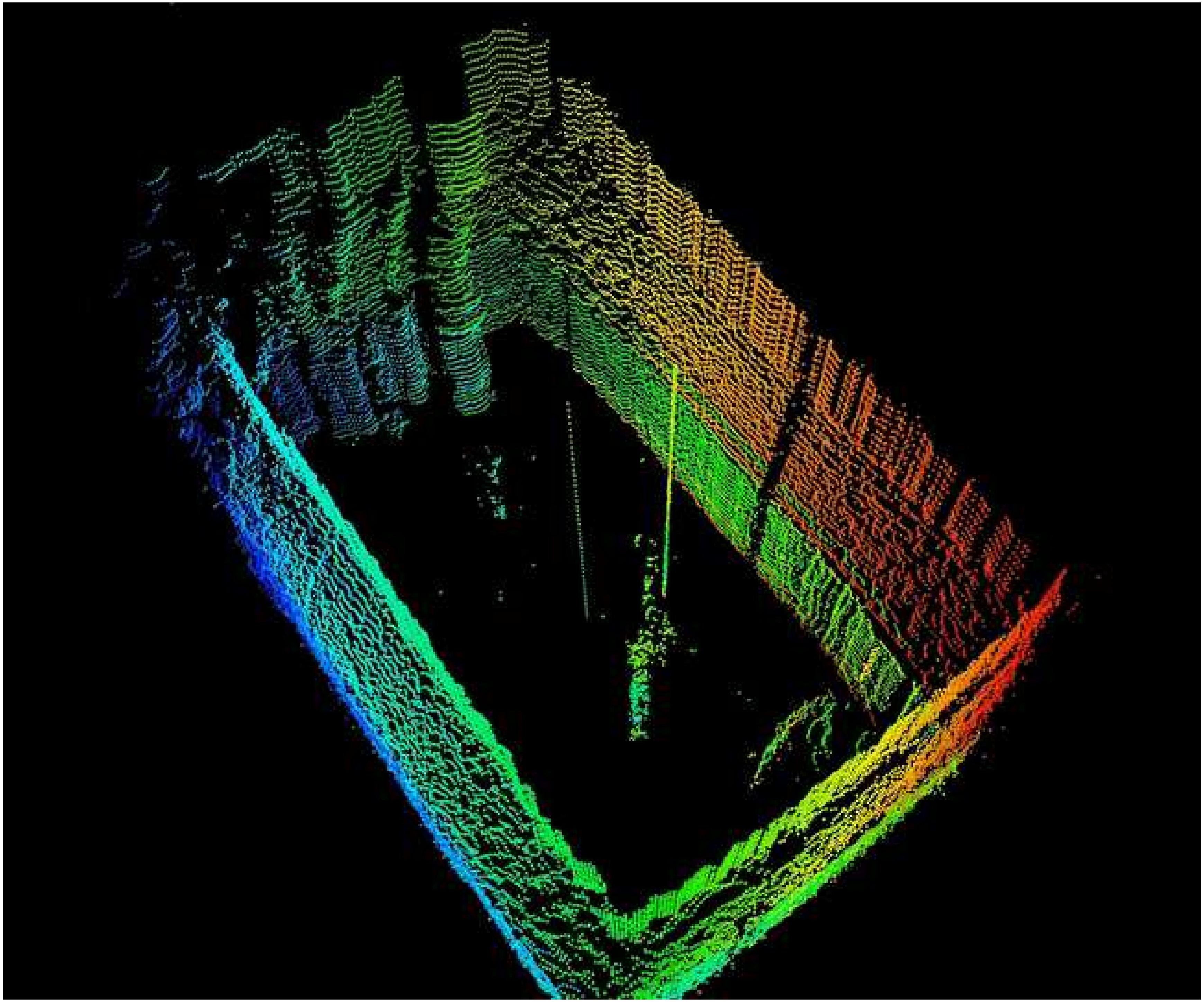


Figure 5

Figure 6

Figure 7 Left

Figure 7 Right

Figure 8 Top Left

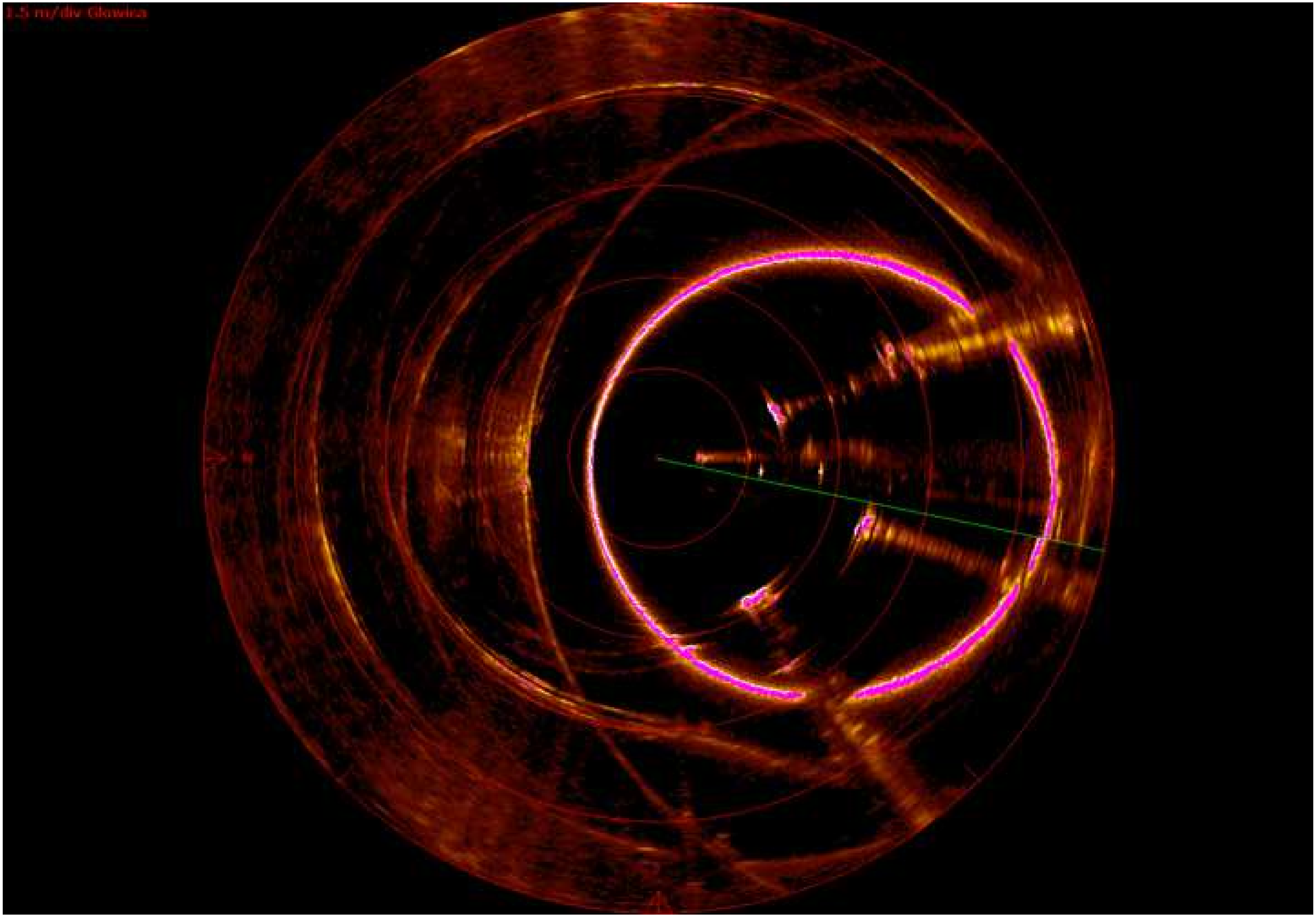


Figure 8 Top Right

Click here to access/download;Colour figure (online version only);Figure 8 top right.png

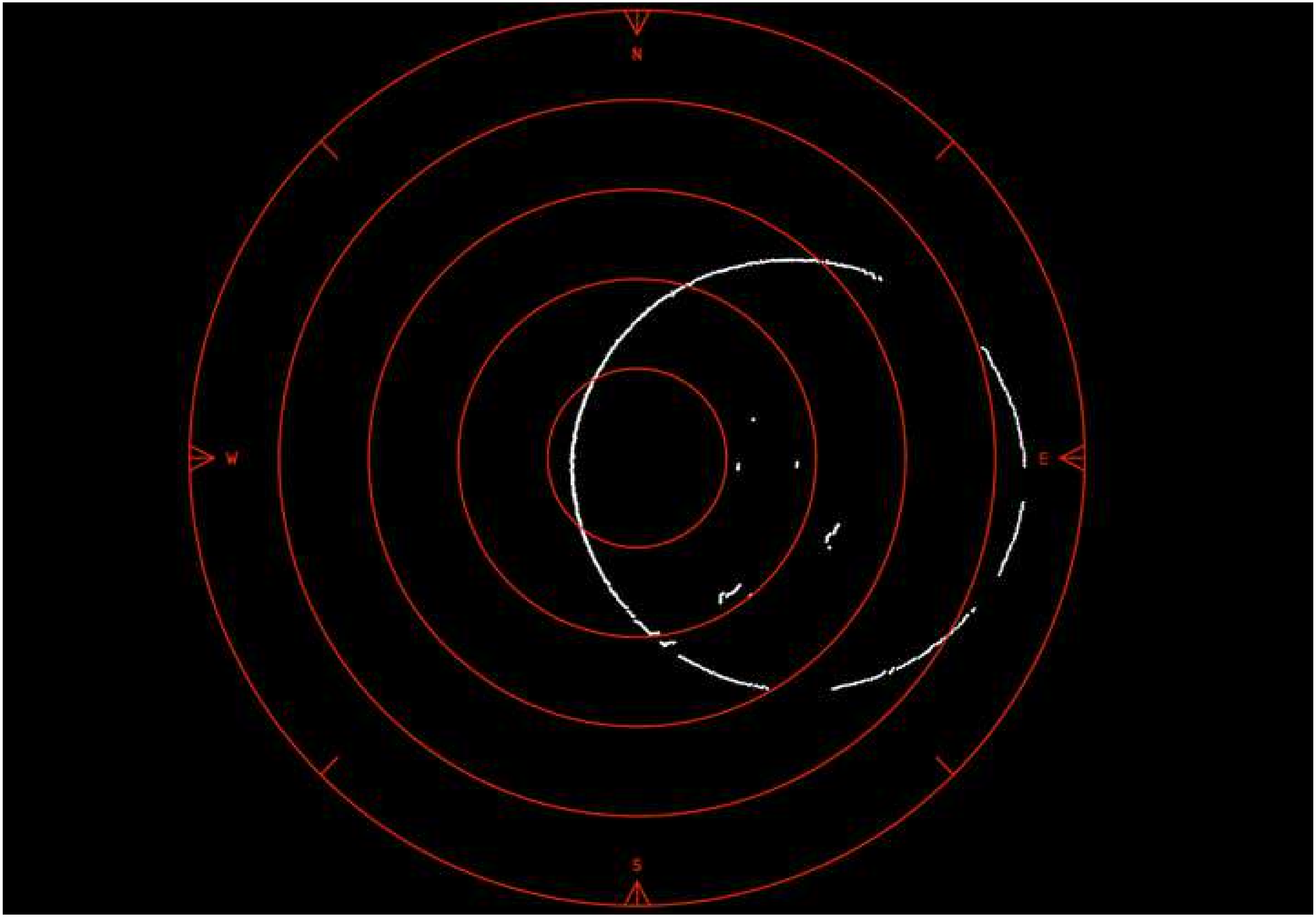


Figure 8 Bottom Left

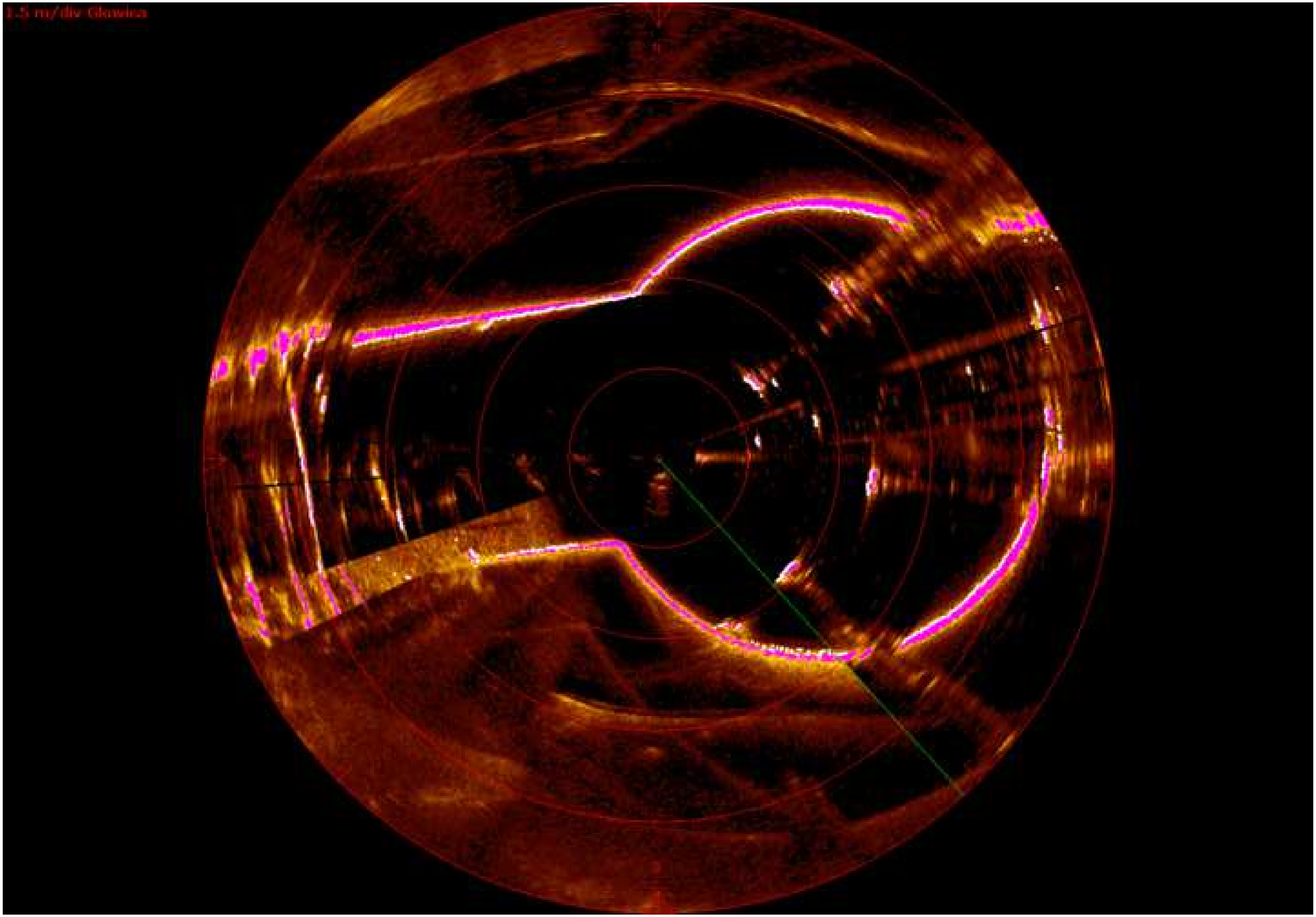


Figure 8 Bottom Right

Click here to access/download;Colour figure (online version only);Figure 8 bottom right.png