Underwater Inspection of Bridge Substructures Using Underwater Imaging Technology

TRANSPORTATION POOLED FUND
RESEARCH STUDY TPF-5 (131)

Literature Review Report

(Select Portions to be used in Final Study Report)

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LITERATURE REVIEW
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TABLE OF CONTENTS

PAGE

APPENDICES

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS AND SYMBOLS

ADCI – Association of Dive Contractors International
ASCE – American Society of Civil Engineers
ASTM – American Society for Testing and Materials (a.k.a. ASTM International)
AUV – Autonomous Underwater Vehicle
DGPS – Differential Global Positioning System
DHS – Department of Homeland Security
DOT – Department of Transportation
FAA – Federal Aviation Administration
EM – Engineering Manual (Published by USACE)
FBI – Federal Bureau of Investigation
FHWA – Federal Highway Administration
GPR – Ground Penetrating Radar
GPS – Global Positioning System
NAUI – National Association of Underwater Instructors
NBI – National Bridge Inventory
NBIS – National Bridge inspection Standards
NOAA – National Oceanic and Atmospheric Association
NHI – National Highway Institute
OSHA – Occupational Safety and Health Administration
PADI – Professional Association of Diving Instructors
PDIC – Professional Diving Instructors Corporation
ROV – Remotely Operated Vehicle
RTK – Real Time Kinematic
SAR – Synthetic Aperture Radar
SSA – Surface Supplied Air
SSI – Scuba Schools International
TA – Technical Advisory
TDI – Technical Diving International
TPF – Transportation Pooled Fund
USACE – United States Army Corps of Engineers
USCG – United States Coast Guard
USGS – United States Geological Survey
WAAS – Wide Area Augmentation System
YMCA – Young Men’s Christian Association

1.0 EXECUTIVE SUMMARY

The requirements for underwater bridge inspection procedures by use of divers are well documented within the United States. Yet some bridge inspectors and owners have increasingly been supplementing diving methods with acoustic imaging technology to enhance inspection quality, increase safety, as well as improve efficiency and documentation of results. This trend has been accelerated because of the technological advancements in sonar devices and the continued need of some bridge owners to inspect bridges with adverse site conditions, such as zero underwater visibility, high velocity currents, submerged debris, and extreme water depth. Because these factors can limit a diver's ability to thoroughly inspect a bridge below water, acoustic imaging technology has been used as a supplement to ensure a thorough inspection. However, there is currently no government guidance on the use of acoustic imaging on bridges.

This Literature Review Report is the first task under Phase I of the Transportation Pooled Fund Research Study TPF-5 (131). The scope of this research study aims to help clarify the quality of data that commercially-available acoustic imaging devices are capable of producing and to demonstrate how this data compares with inspection findings documented by a qualified underwater inspection diver. Research efforts will focus on quality efficiency of data that can be obtained by various acoustic imaging devices in swift currents, deep waters, and in zero visibility situations. Additionally, time and cost associated with each field procedure will be tracked for comparison.

Potential applicability of acoustic imaging for bridge inspections includes:

- Rapid condition assessment (e.g., post-seismic events, vessel impact inspection)
- Scour detection and documentation (e.g., channel bottom and foundation exposure information)
- Underwater construction inspection (e.g., quality control, progress payments, pre-/post site conditions)
- Security threat assessment (e.g., detection of submerged explosives, intruder detection)
- Documented visual representation of an entire underwater structure (e.g., as-built plans, large scale defects)
- Diver safety and efficiency enhancement at challenging dive sites (e.g., fast current, heavy debris, extreme depth, polluted water, and dangerous wildlife)

Assessment of the available body of knowledge on this topic indicated the need for additional documented case studies and scientific review of the advantages and limitations of acoustic imaging. Several conclusions were derived from this literature review including:

- Sonar technologies can be economically and easily employed at bridge sites to assist in the above listed inspection applications.

- Based on the varying needs of bridge owners, the literature suggests that no single acoustic imaging technology is appropriate for every situation.

- Many variables affect the accuracy and resolution of an acoustic image including construction material type, substructure geometry, and site specific environmental factors. For this reason, laboratory image testing of fabricated replica materials and defects may not accurately simulate the vast array of conditions present at real bridge sites.

- Government guidance, standards, and regulations are warranted on this topic.

- Research, dissemination of information, and education of end users is important to progress the use of acoustic imaging from exploration to acceptable field deployment.

2.0 INTRODUCTION

2.1 BACKGROUND INFORMATION

The collapse of the Silver Bridge in 1967 prompted Congress to prepare the Federal-Aid Highways Act of 1968 which required establishment of a national bridge inspection standard and a program to train bridge inspectors. In April 1985, the US-43 Bridge over Chickasawbogue Creek in Alabama collapsed, causing officials to issue steps ensuring that each state had an underwater bridge inspection program in place. Following the tragic collapse of the Schoharie Creek Bridge in New York in 1987, the Federal Government implemented revisions to the National Bridge Inspection Standards (NBIS) which, among other things, made underwater bridge inspection a mandatory practice.

Federal Highway Administration (FHWA) Technical Advisory (TA) 5140.21 "Revisions to the NBIS" was issued on September 16, 1988 and provided guidance on underwater bridge inspections. This TA recognized that technology might advance, leaving the method for underwater bridge inspections open-ended by stating "inspections in deep water will generally require diving or other appropriate techniques to determine underwater conditions".[1] The TA goes on to further state that "the underwater inspection requirements of Title 23 Code of Federal Regulations Section 650.303 pertain to inspections that require diving or other special methods of equipment". [1] However, it has been common practice that any technique, other than diving, receives approval from FHWA. For example, Washington DOT and Colorado DOT have obtained approval from their FHWA Division Office to utilize camera-mounted remotely operated vehicles (ROV's) to supplement divers for underwater inspections in water depths exceeding 120 feet. Although the NBIS and TA 5140.21 does not specifically state the need for FHWA approval on the type of "special methods" and "advanced technologies" used to complete an underwater inspection, FHWA concurrence on methods is required to ensure the "required level of certainty" [1] mandated in TA 5140.21 as part of their oversight of the highway agency inspection program.

TA 5140.21 describes the following three levels of intensity effort for routine underwater bridge inspections:

- **Level I** – A "swim-by" overview, with minimal cleaning to remove marine growth which should be performed on 100% of the underwater portion of the structure.

- **Level II** – Limited measurements of damaged or deteriorated members which should be conducted on 10% of underwater units and requires removal of marine growth for closer examination.

- **Level III** – Highly detailed inspection utilizing nondestructive tests such as ultrasound or minimally destructive tests such coring of wood or concrete. Level III effort is to be performed on an as needed basis if Level I and Level II efforts are inconclusive.

While the regulations and guidance covering underwater bridge inspections by use of divers are well documented by the FHWA, commentary associated with utilizing underwater acoustic imaging for bridge inspections is only introduced for informational purposes in the FHWA Underwater Bridge Inspection Manual.[2] Nonetheless, several highway agencies have utilized underwater acoustic imaging and have requested guidance from the FHWA on the use of this technology. In 2009, the FHWA's Technical Resource Center responded to highway agencies regarding the use of acoustic imaging for underwater bridge inspections in an email memo issued by C. Nurmi stating that Research Study TPF-5 (131) "Underwater Inspection of Bridge Substructures Using Underwater Imaging Technology" was being planned to assess the use of sonar technology during bridge inspections. The memo further stated that "the FHWA would address any policy/guidance or regulatory issues regarding the use or substitution of sonar for underwater inspections by divers after their research is completed".[3] Until Research Study TPF-5 (131) has been completed and FHWA has evaluated the findings, bridge owners were informed that sonar technology could be used only to supplement bridge inspection diving operations (i.e., to document findings in conjunction with their Level I and Level II efforts), and in situations where underwater inspections cannot be safely performed by divers since some information is better than no information. However, the memo clearly stated that sonar results alone are not allowed as a substitute for the data obtained by a qualified diving inspector with the appropriate intensity levels, as outlined by FHWA guidelines.[3] Therefore, research study TPF-5(131) is aimed at studying the effectiveness of acoustic imaging technologies for underwater inspection of bridges by clarifying the quality, accuracy, and repeatability of data that commercially-available acoustic imaging devices are capable of producing and by demonstrating how this data compares with inspection findings documented by a qualified underwater inspection diver.

According to the 2011 National Bridge Inventory (NBI) data, there are 712,344 bridges in the United States, and 609,729 of these structures span waterways. Additionally, state highway agencies oversee 31,148 bridges with submerged substructures that require an underwater bridge inspection with approximately 7,580 of these bridges being scour critical.[5] Furthermore, there are numerous additional bridges requiring underwater inspections under the jurisdiction of various federal agencies including FHWA, U.S. Department of Defense, U.S. Bureau of Reclamation, U.S. Bureau of Indian Affairs, U.S. Forest Service, and others. Table 1 summarizes the total number of bridges in each state jurisdiction requiring an underwater inspection as well as the number of scour critical bridges.

In 1981, only 15 state transportation agencies routinely conducted underwater bridge inspections.[6] As a result of the 1988 NBIS [1] revisions requiring underwater bridge inspections, all state transportation agencies now require and ensure underwater inspections of their submerged bridge substructures, as well as oversee the underwater bridge inspection program at the local level. Since the implementation of the NBIS requirements for underwater bridge inspections, there has been significant amounts of technical information presented on the topic in addition to TA 5140.2. The FHWA Manual titled *Underwater Inspection of Bridges* was published in 1989 and was distributed in conjunction with nationwide bridge inspection demonstration training sessions (FHWA Demonstration Project 80 – *Bridge Inspection Techniques and Equipment*). In the 1990's, FHWA Training Demonstration Project 98 - *Underwater Evaluation and Repair of Bridge Components* was offered nationwide.

Table 1. Summary of bridges requiring underwater inspections.[5]

Agency	Bridges Requiring Underwater Inspections	Scour Critical* Bridges Requiring Underwater Inspections
ALABAMA	915	262
ALASKA	186	119
ARIZONA	16	6
ARKANSAS	3951	302
CALIFORNIA	662	67
COLORADO	97	13
CONNECTICUT	332	71
DELAWARE	127	12
DIST. OF COL.	56	0
FLORIDA	4143	1254
GEORGIA	2113	1353
HAWAII	174	56
IDAHO	316	151
ILLINOIS	531	30
INDIANA	679	43
IOWA	143	5
KANSAS	155	16
KENTUCKY	137	6
LOUISIANA	1335	609
MAINE	383	56
MARYLAND	432	21
MASSACHUSETTS	746	247
MICHIGAN	331	109
MINNESOTA	386	49
MISSISSIPPI	340	98
MISSOURI	160	17
MONTANA	429	27
NEBRASKA	99	35
NEVADA	64	35
NEW HAMPSHIRE	193	38
NEW JERSEY	727	91
NEW MEXICO	1	1
NEW YORK	862	124
NORTH CAROLINA	2467	714
NORTH DAKOTA	47	4
OHIO	385	9
OKLAHOMA	69	3
OREGON	1004	581
PENNSYLVANIA	2140	527
RHODE ISLAND	98	43
SOUTH CAROLINA	242	29
SOUTH DAKOTA	132	48
TENNESSEE	526	111
TEXAS	115	49
UTAH	39	3
VERMONT	57	4
VIRGINIA	715	7
WASHINGTON	379	82
WEST VIRGINIA	844	15
WISCONSIN	587	14
WYOMING	55	8
PUERTO RICO	26	6
TOTAL	**31,148**	**7,580**

*Includes bridges built on unknown foundations

In 2001, the American Society of Civil Engineers (ASCE) published *Standard Practice Manual 101 – Underwater Investigations*. Following the revision of the NBIS in 2004 (effective 2005), the National Highway Institute (NHI) developed the Underwater Bridge Inspection Course 130091. In 2010, the NHI completed development of a comprehensive state-of-the-art reference manual to replace the 1989 FHWA Underwater Bridge Inspection Manual, and updated NHI course 130091 with additional information including some underwater imaging technologies. Additionally, there have been numerous FHWA publications and training courses related to scour detection, scour evaluation, and scour repair design; but no formal guidance on the use of acoustic imaging at bridges.

In the past, studies have been conducted on the reliability of bridge inspection techniques and various research projects have investigated the possible integration of advanced technologies in the activities for structural inspections above and below water. However, these efforts have been selective and incomprehensive with regards to several underwater acoustic imaging devices. Nonetheless, much interest has been shown by several state highway agencies and a host of security related agencies including the Department of Homeland Security (DHS), United States Geological Survey (USGS), Federal Bureau of Investigation (FBI), and National Oceanic and Atmospheric Administration (NOAA).

2.2 OVERVIEW OF UNDERWATER IMAGING

Underwater imaging is a general concept that encompasses a wide variety of technologies. Underwater photography and underwater videography are the two most commonly used methods for obtaining underwater still images and underwater video. However, water clarity greatly affects the quality of the images obtained by these two optical means. Furthermore, the camera range and lighting for underwater photography and videography often prohibit a large panoramic view, as well as only providing a two-dimensional (2-D) perspective. Non-optical technologies that have demonstrated success in providing underwater images include sonar, laser, and radar. Laser scanning (often referred to as Lidar in above-water applications) can produce extremely accurate underwater images, but possess limited range due to light transmission factors related to water clarity and other limitations make it more widely used for offshore ocean structures than inland waterway bridges. Radar technologies, such as ground penetrating radar (GPR), can produce underwater images primarily of internal concrete defects or subsurface channel-bottom geotechnical strata layers, while synthetic aperture radar (SAR) has been used to obtain large-area perspective underwater imaging of channel-bottom topography.[4]

Of all the non-optical underwater imaging technologies, sonar has demonstrated the most potential and is the most widely used for bridge inspection applications. Even in the most turbid waters with zero visibility, sonar can provide depth data and high-quality images. Since sonar technology utilizes sound waves, it is known as an acoustic technology. Underwater acoustic images vary in quality, resolution, and dimensional perspective (2-D or 3-D) depending on the particular sonar device. Because sonar shows the most potential for bridge inspection applications, this research concentrates primarily on sonar-related technologies, although other related technologies are briefly mentioned.

2.3 CURRENT UNDERWATER BRIDGE INSPECTION PRACTICES

The NBIS have specific sections related to application of standards (23CFR650.303), inspection procedures (23CFR650.313), frequency of inspections (23CFR650.311), qualifications of personnel (23CFR650.309), and inventory (23CRF650.315), as well as expectations for inspection reports. While all of the similarities and differences between states are not covered herein, a variety of policies have been established and implemented by each agency to comply with the requirements of the NBIS with regards to underwater inspections.[8]

2.4 QUALIFICATIONS AND CERTIFICATION OF PERSONNEL

There are well-defined qualification standards for both the necessary inspection skills and diving skills required to conduct an underwater bridge inspection by divers. However, there are no specific required qualifications or certification processes for the use of acoustic imaging devices. There are some related, but non-applicable, standards for sonar use in the hydrographic surveying industry; in particular, the U.S. Army Corps of Engineers (USACE) has established sonar procedures in EM 1110-2-1003 Hydrographic Surveying and the American Congress on Surveying and Mapping (ACSM) administers exams for Certified Hydrographers, but these organizations exclude underwater acoustic imaging. American Society for Testing and Materials (ASTM) International Committee E57 does set standards for 3-D imaging but the criteria to-date has only been focused on above water laser scanning and Lidar.

Underwater inspection divers are generally categorized as either engineer-divers or construction-divers. This categorization is derived from the fact that engineer-divers have college-level degrees in engineering (generally civil / structural), and construction-divers have skilled-trade training in activities like welding, concrete placement, pipework, etc. In order to be qualified to inspect a bridge in accordance with the NBIS, both groups are required to have completed a comprehensive bridge inspection training course (FHWA-NHI-130055 entitled Safety Inspection of In-Service Bridges, or approved equal), or the NHI Underwater Bridge Inspection Course 130091. Furthermore, the inspection team leader must have completed a comprehensive bridge inspection training course and meet the educational/experience requirements outlined in the NBIS. In addition to the federal requirements, various states have more stringent requirements for an underwater inspection diver and for an inspection team leader. For example, some state highway agencies require all divers to have completed the NHI Underwater Bridge Inspection Course 130091 and that the team leader physically dive a certain percentage of the bridge. While the above text discusses qualifications, a number of state highway agencies (including MN and OR) actually certify bridge inspectors with competency exams. It is important to highlight here, the difference between “qualified” and “certified”.

OSHA 29CFR1910 Commercial Diving Regulations requires underwater diving operations to be performed by personnel trained in the specific tasks assigned.[7] OSHA allows both commercial scuba and surface supplied air (SSA) diving for underwater operations. The Association of Diving Contractors International (ADCI) publishes Consensus Standards on best practices, which also has provisions for the use of both scuba and SSA diving for underwater operations.

OSHA Directive CPL 02-00-151 titled 29 CFR Part 1910, Subpart T – Commercial Diving Operations was published on June 13, 2011 to clarify acceptable dive training and regulations.[7]

Currently, both scuba and SSA dive modes are frequently used by public-sector and private-sector dive teams. Nonetheless, OSHA Directive CPL 02-00-151 requires formal commercial diver training. Recreational diving certifications such as NAUI, PADI, YMCA, TDI, SSI, or PDIC are not recognized by OSHA as meeting the requirements for commercial dive training.

While recreational sport divers, scientific divers, and many government agencies such as emergency fire/rescue/police may be outside the jurisdiction of the federal OSHA Regulations, they are not exempt from OSHA Regulations while performing underwater bridge inspections since that technical work is not related to their exempted primary nature of activities.[2]

2.5 LITERATURE REVIEW METHODOLOGY

As part of the research efforts, a literature review was conducted to examine previous studies and gather pertinent information. Various sources were searched for information including all applicable codes, major university databases, National Academies Databases, National Transportation Library Database, USACE Engineering Manual Library, ASCE's Cybrarian Research Service, the internet, equipment manufacturer specifications data sheets, and various international sources. Some of these references were utilized in summarizing the existing knowledge base and are cited numerically in Appendix A and referenced throughout the text of this report. Appendix B contains additional reference material that was reviewed but not cited.

The literature search revealed many technical papers and publications on "underwater imaging" and "underwater acoustic"; however, the vast majority of the topics were related to theoretical concepts (e.g., signal processing, oceanography, beam propagation, etc.) and non-bridge specifics (e.g., ocean mammal monitory, underwater communications, marine aquaculture, etc.). Only the most relevant works to this study have been included in Appendix A and Appendix B.

3.0 BASIC ACOUSTIC THEORY

3.1 GENERAL

The principles and mathematical concepts governing sonar and underwater acoustics are readily available in numerous texts; as such, the intent of this document is not to reiterate this detailed information. Rather, the intent is to present the principles in a manner that will help government agencies, program managers, and bridge inspectors understand the capabilities and limitations of various sonar devices and apply them to evaluating these technologies.

For the purposes of explaining the basic theories of acoustics, water depth measurements with sonar are frequently discussed in this section. It should be noted that basic water depth measurements and high definition sonar images of bridge substructures are both governed by the same acoustic theory principles.

3.2 HOW SONAR WORKS

The term sonar originated as an acronym for "SOund NAvigation and Ranging". In the simplest sense, sonar works by emitting an acoustic pulse (sound) into the water column and measuring the amount of time that the sound wave takes to bounce off of a target and return to the source. In most sonar applications used in science and industry, the transducer serves several functions. When the system wants to produce a sonar "ping", the transmitter generates an oscillating electric signal with frequency characteristics that can be uniquely distinguished. The transducer converts the electrical energy into sound waves. In this capacity, it is being used as a projector. The oscillating electric signals are converted into mechanical vibrations that are transmitted into the water as an oscillating pressure or a sound wave. Upon its return as an echo from the sea floor, the sound pulse is received and converted back into electrical signals by the transducer acting as a hydrophone.[9]

Sound travels through water in a series of pressure waves known as compression waves. These pressure waves propagate at a constant speed through a uniform water environment. The distance between pressure waves is referred to as the wavelength. The number of pressure fronts that pass a stationary point in the water per second is the frequency and it is measured in Hz or kHz.[9] Refer to Figure 1 for a graphical representation of sonar terminology.

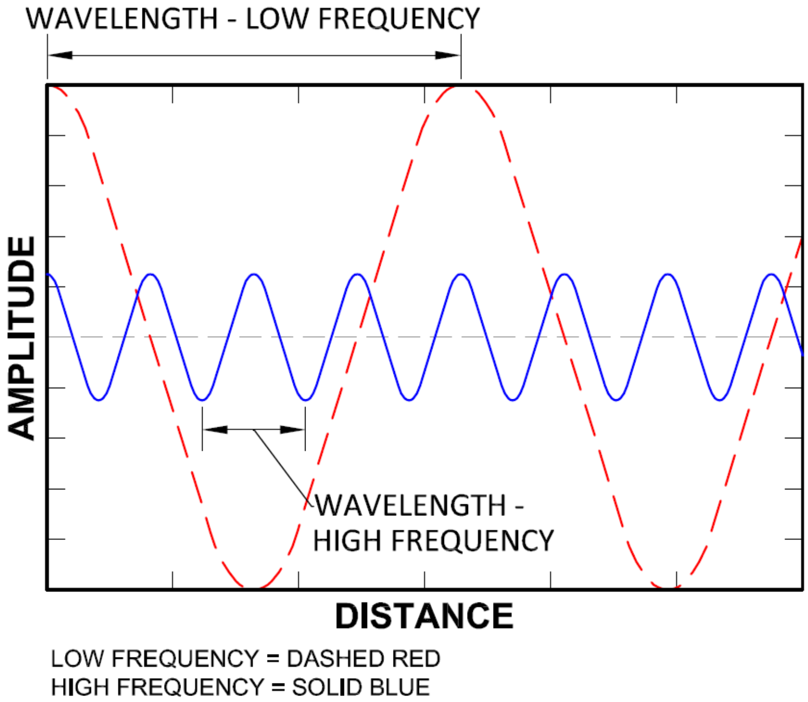

Figure 1. Graphic plot of low and high frequency sound waves.

3.3 TRANSDUCER CONE ANGLE, BEAM SHAPE, AND SIDE LOBES

When a sonar transducer emits an acoustic pulse, the sound travels through the water in an inverted dome pattern in all directions. The pulse is strongest directly below the transducer, and weakens as the angle from the central axis increases. A transducer's cone angle refers to how centrally focused or spread out the acoustic beam is arranged. The cone angle is defined as the distance from the central axis to the point of half power.[9] This effect can be related in non-acoustic terms to a flashlight and a laser pointer each being pointed at a wall. The flashlight (wide cone angle) illuminates a large area while the laser pointer (small cone angle) focuses on a finite point.

When performing hydrographic surveys or gathering bridge sounding depth data, it is typically desirable to get the best possible reading directly below the transducer so the smallest available cone angle is usually preferred. On the contrary, if a sonar operator wished to find the shallowest point or an obstruction in a channel, a wider cone angle would be selected to ensure that the entire channel bottom is covered. Transducer cone angles can also take on elliptical or even fan shapes.

Another aspect of sonar beam shape is an attribute known as side lobes. Side lobes exist in all sonar beams and consist of weaker misdirected energy that is projected to the sides of the main lobe. Side lobes can cause return echoes that may be misinterpreted especially when working near vertical surfaces.[9] Refer to Figure 2 for a graphical representation of sonar cone angle and side lobes.

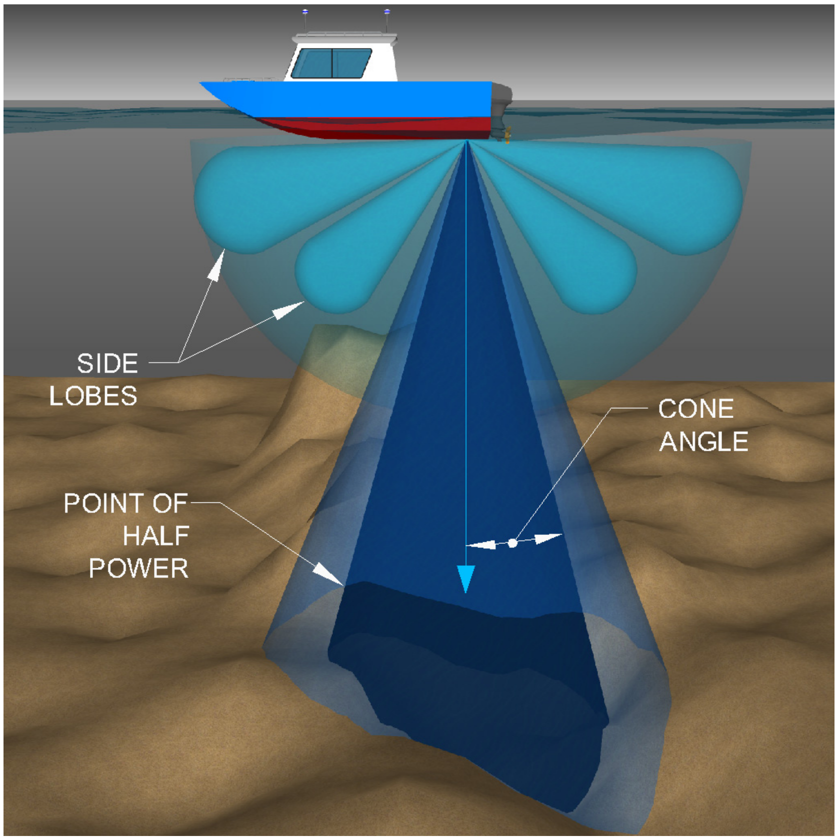

Figure 2. Depiction of sonar cone angle and side lobes.

3.4 VELOCITY OF SOUND THROUGH WATER

The most basic sonar systems assume that the water environment is uniform and that the rate of sound does not change from one area to the next. In reality, this assumption is seldom the case. The major influence affecting the velocity of sound in water is the water's density, which changes with depth, temperature, and salinity. Acoustic theory textbooks show that the speed of sound in water changes by the following units:[10]

- 100 ft change in depth = 1.7 ft/sec change in velocity
- 1° F change in temperature = 6.4 ft/sec change in velocity
- 1ppt change in salinity = 4.6 ft/sec change in velocity

For any combination of these conditions, the speed of sound has a constant and determinant value. However, if any of the conditions change, the speed of sound in the new environment will also be affected accordingly. When the speed of sound changes from one environment to another, the wavelength changes proportionally, but the frequency remains constant.[10]

Assuming that fresh water has a salinity of approximately 0.5 parts per thousand (ppt) and that the ocean has a salinity of approximately 35 ppt, we can analyze how the combination of these three factors affect the overall depth reading that a sonar device will produce. The below simplified example assumes that the water column of each environment has constant properties throughout. In Table 2, Environments No. 2 through No. 4 show the change in measured depth error from baseline Environment No. 1 (5 ft deep) that would be expected if corrections were not made. In Table 3, Environments No. 6 through No. 8 show the change in measured depth from baseline Environment No. 5 (200 ft deep) that would be expected if corrections were not made. The highlighted values in each table identify the variables that have changed in each example.

Table 2. Effects of depth, temp., and salinity on sonar at 5 ft.

Environment	Temperature (°F)	Salinity (ppt)	Speed of sound (ft/s)	Depth error from baseline Environment No. 1
1. Fresh Water (Baseline)	35	0.5	4627	0 ft
2. Fresh Water	85	0.5	4947	0.3 ft
3. Ocean Water	35	35	4779	0.2 ft
4. Ocean Water	85	35	5067	0.5 ft

Table 3. Effects of depth, temp., and salinity on sonar at 200 ft.

Environment	Temperature (F)	Salinity (ppt)	Speed of sound (ft/s)	Depth error from baseline Environment No. 5
5. Fresh Water (Baseline)	35	0.5	4637	0 ft
6. Fresh Water	85	0.5	4958	13.9 ft
7. Ocean Water	35	35	4789	6.6 ft
8. Ocean Water	85	35	5077	19.0 ft

By comparing the speed of sound values of Environments No. 1 and No. 5, or (No. 2 and No. 6, etc.), the reader can see that depth will not be a significant source of error since most bridges are built in less than 200 feet of water. The approximate difference in speed of sound of between Environments No. 1 and No. 5, where depth is the only variable, is only 10 ft/s which relates to about 0.1 foot error. By comparing values from Environments No. 5 and No. 6, the reader can see that if a thermocline exists at a bridge or if incorrect temperature data is assumed, the result is the potential for significant error in depth data.

Salinity of the water around a bridge site is typically held near a constant value. Exceptions to this rule are for bridges located in brackish water, near tidal currents, or large discharge pipes. If a halocline (separation of water layers with differing salinity levels) exists within the water column, a moderate change in water velocity can be expected between the water layers. A comparison of results from Environments No. 5 and No. 7 shows that even if salinity is held constant at a bridge site, moderate depth measurement errors can be expected if an incorrect salinity value is assumed. For a typical water column with varying depth and temperature, a sound velocity profile will resemble the graph in Figure 3.

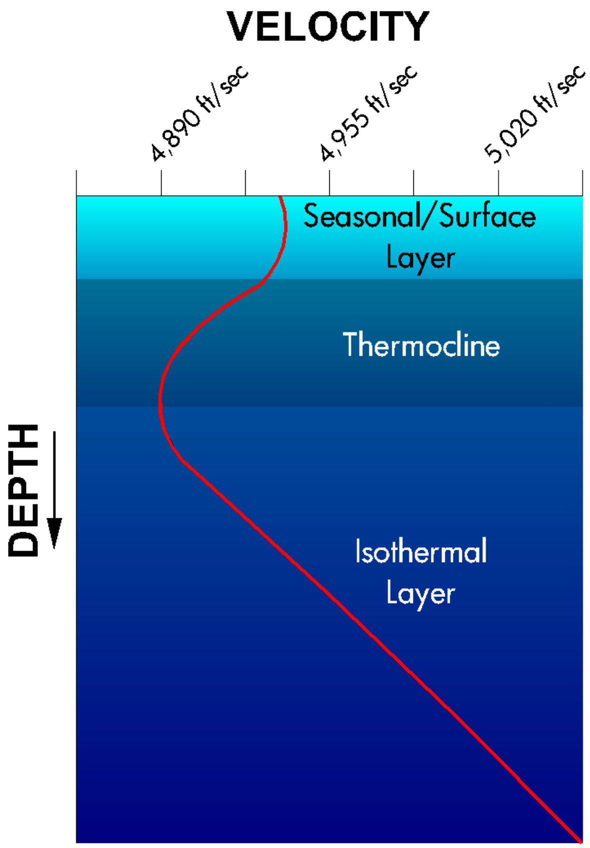

Figure 3. Typical sound velocity profile.

3.5 REFRACTION OF SOUND TRAVELING THROUGH WATER

In addition to the velocity of sound changing as it progresses through the water column, the angle of a sound wave also changes as it crosses between environments of different density. This phenomenon is known as refraction. The result is that an acoustic pulse that is sent downward from a boat may actually hit the channel bottom or other target at a location that is not directly below the transducer. When a sound wave enters a region of lower sound velocity, the wave bends toward the vertical axis. When a sound wave enters a region of higher sound velocity, the wave bends away from the vertical axis. This process affects both the emitted pulse and the return echo. If not accounted for, or properly analyzed, the resulting interpretation can lead to inaccuracy in both depth and position measurements.[9] Figure 4 illustrates the path sound takes as it travels through water layers with varying properties.

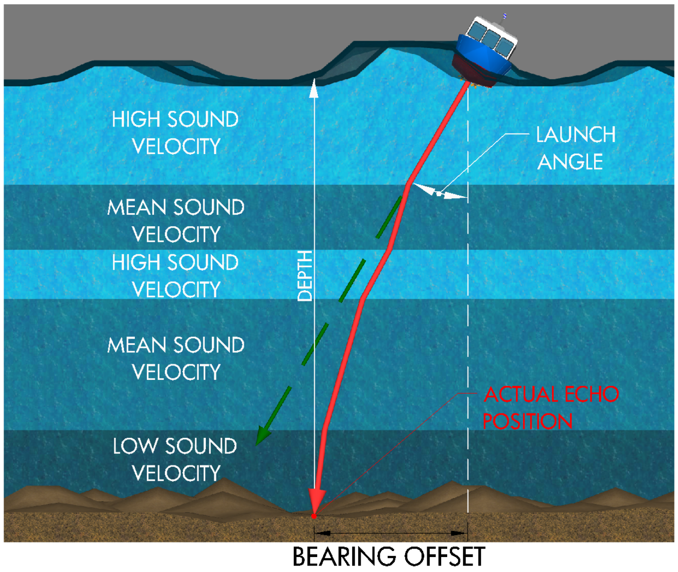

Figure 4. Direction of sound wave through varying water layers.

3.6 STRENGTH OF RETURN ECHOES

Sound loses energy as it travels through the water (a process known as attenuation) for several reasons. Losses occur from the sound wave spherically spreading and thinning over distance and from striking particles or objects in the water column. In general, sound loses energy faster in salt water than in fresh water. The ability of sound to maintain energy as it travels is primarily a function of frequency. High frequency sound tends to lose energy faster than low frequency sound. This fact is why lower frequencies are used in sonar when it is desirable to penetrate through layers of sediment, extremely turbid water, or for long distance communication. On the other hand, higher frequencies are typically more desirable for high definition imaging applications because they have smaller more defined sound waves.[9] Figure 5 illustrates how range and resolution change with frequency.

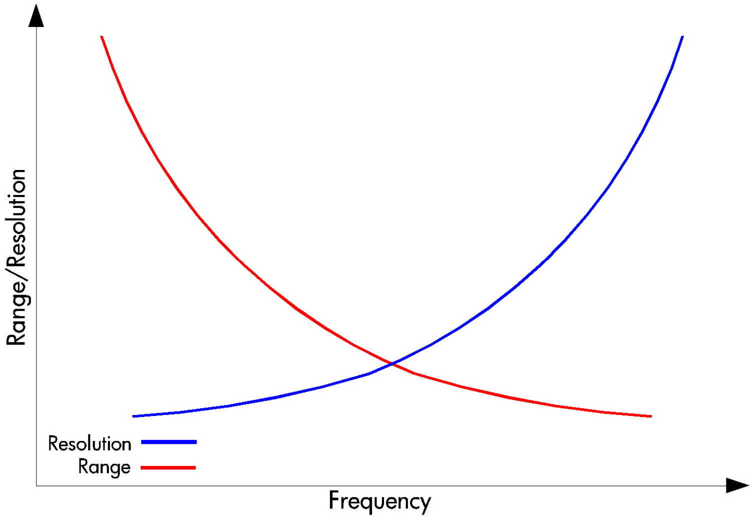

Figure 5. Relationship of range and resolution with varying frequency.

Sound also loses energy every time it bounces off of an object. The amount of the sound that is absorbed and the amount that bounces off of the target depends on the object's acoustic reflectivity. Acoustic reflectivity depends on the frequency of the sonar being used, pulse duration, the incident angle, acoustic roughness, composition of the target, as well as the size, thickness, and shape of the target. The sound absorption coefficient indicates the amount of the sound that is absorbed into the actual material and is expressed as the ratio of the absorbed sound energy to the incident energy and varies with the frequency of the sound. This implies that full absorption would be 1.0 and full reflection would be 0.0.[11]

In general, bridge construction materials with an internal speed of sound that are much different than water tend to be good reflectors. For this reason, sonar imaging of concrete, masonry, or steel bridge substructures can generally be expected to produce strong returns. On the other hand, saturated timber formwork, old timber piles, and some types of rubber fender material have much higher sound absorption coefficients and reflect very little acoustic energy, and in some cases, may actually produce an image resembling a void. Marine growth on the material will also affect the sound absorption. Similarly, rock or gravel channel bottoms have a lower sound absorption coefficient than sand or silt, and thus solid/large aggregates are better reflectors.[11]

As previously stated, sonar works by emitting an acoustic pulse into the water column and measuring the amount of time that sound takes to bounce off of a target and return to the instrument. In reality, the sound does not bounce off of the object in a clean and consistent manner. Some of the sound is absorbed by the object and some reflects off of the target and scatters in all directions. The amount of the sound that reflects back in the direction of the sonar receiver depends on the angle at which the pulse hits the target. This characteristic is referred to as the angle of incidence, and is measured as the angle between a line perpendicular to the face of the target and a line from the transducer to the target.[9] Figure 6 illustrates the components of a sonar echo event.

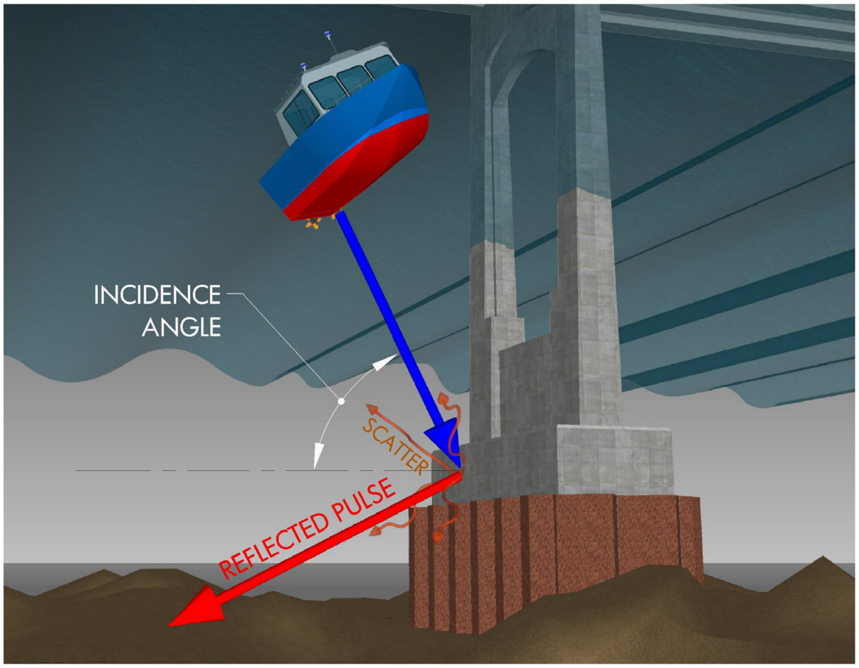

Figure 6. Components of sonar echo event.

As depicted in Figure 7, if the angle of incidence to a flat surface is 0 degrees, the majority of the energy is reflected back to the transducer. A round target tends to scatter most of the sound in an undesirable direction. However, a round target is also the only shape that guarantees a portion of the surface to have an incident angle of 0 degrees relative to the transducer. When a target has a round surface, the ability to detect the outside limits of the target becomes less as the angle of incidence increases because more energy is reflected away from the transducer in an undesirable direction. This fact is the primary reason that round bridge piles are more difficult to image with sonar than large rectangular pier shafts. Additionally, heavy surface texture of the target can cause the energy to scatter in unpredictable directions.[11] Example of heavy surface texture include stone masonry, scaled concrete, or an architectural form-liner produced concrete surface finish.

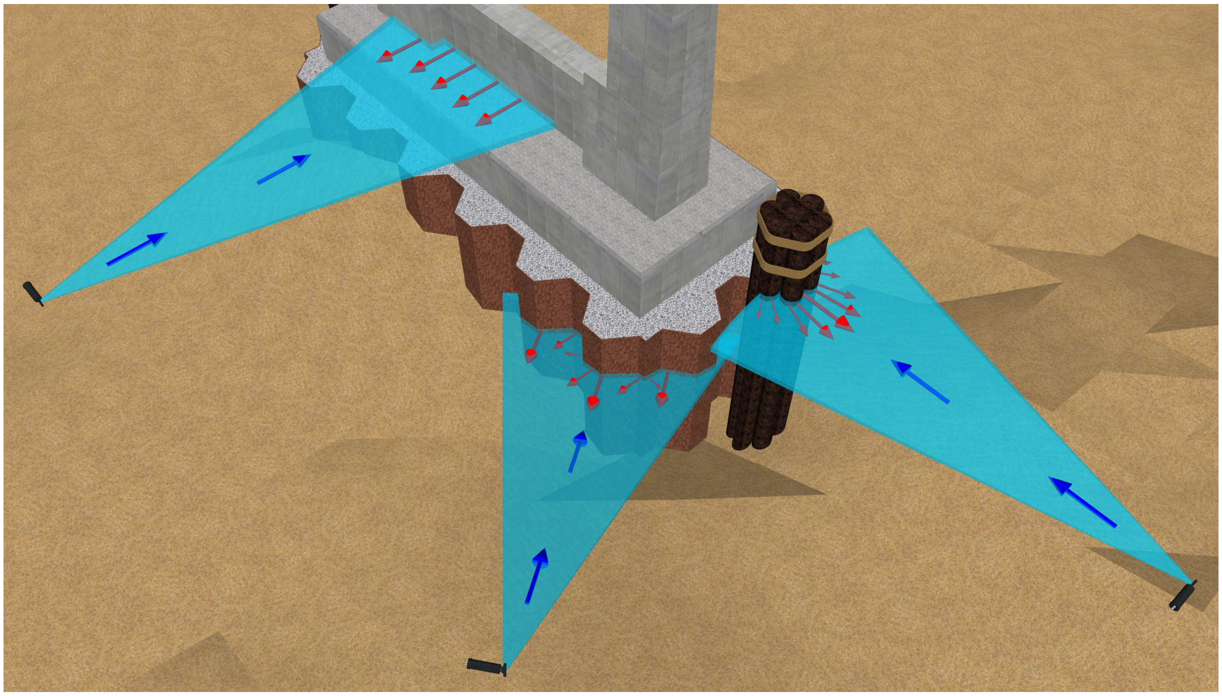

Figure 7. Effect of target shape on return echo.

4.0 TYPES OF SONAR TECHNOLOGIES

4.1 GENERAL

Sonar technologies can be classified into two broad categories based on the type of data that they produce. Some systems produce two-dimensional data while others produce three-dimensional data. Two-dimensional sonar systems take a three-dimensional space and plot it on a two-dimensional screen. Two-dimensional sonar produces the best definition when the angle of incidence is very high.

Three-dimensional data consists of many data points each with unique x, y, and z coordinates. There is always some amount of interpolation in a rendered sonar image. When discussing three-dimensional data such as that produced by single or multi-beam sonar, the amount of detail that can be generated is dependent upon how small of an area the beam can focus on and obtain a point reading and also upon the number of points that are obtained. The number of data points obtained in an area is referred to as data density. If a particular sonar system has more beams, or a faster ping rate, the ability to obtain more dense data coverage becomes possible in less time. Three-dimensional sonar works best when the angle of incidence is very low.

4.2 THREE-DIMENSIONAL SONAR SYSTEMS

4.2.1 Fathometers/Echosounders

For bridge inspections, water depths can be manually obtained with a sounding pole or lead line, but sonar devices provide more efficiently and effectively retrieved electronic data. The simplest fathometers consist of an acoustic sending/receiving device (transducer) suspended in the water and a digital or paper recording device. Paper strip-chart recorders historically used by recreational fishermen have long been an adapted inspection tool for bridge managers due to its permanent “hard-copy” documentation capability. However, these inexpensive strip-chart recorders are being phased out and replaced by more modern survey-grade precision echosounders.[14]

Fathometers and echosounders are single-beam sonar systems that gather three-dimensional data when connected to a GPS or other geographical coordinate collection system. Fathometer frequencies typically range between 24 kHz and 340 kHz, with higher frequencies yielding higher resolution, but little or no channel-bottom penetration. Because channel-bottom penetration is typically not desired when performing a fathometer survey, a higher frequency of 200 kHz is commonly used.[14]

Table 4 illustrates how large of a footprint various transducer cone angles make on the channel bottom at a given depth.[13] Within this footprint, the strongest echo is usually returned to the unit and recorded as the depth. Depending on the channel-bottom configuration, the strongest echo is not always in the center of the sonar cone. However, the data recorder assumes the strongest echo is at the center of the cone so the true location of the target can be distorted.

Table 4. Approximate footprint of different transducer cone angles in ft^2.

Projected depth	0.75 deg	1.5 deg	4 deg	10 deg
10 ft	< 1	< 1	< 2	10
25 ft	< 1	< 2	10	60
50 ft	< 2	5	40	250
75 ft	3	10	90	550

Because sonar footprints can become quite large at depth, the sonar operator must be careful not to confuse an exposed bridge footing or other submerged obstruction as the channel bottom. With single-beam sonar, the exact location of the return echo is not always known. Figure 8 illustrates a likely scenario for obtaining a false return echo near a bridge pier. Likewise, fathometers will not provide information about the channel-bottom elevation located directly below a footing and cannot provide undermining dimensions.[14]

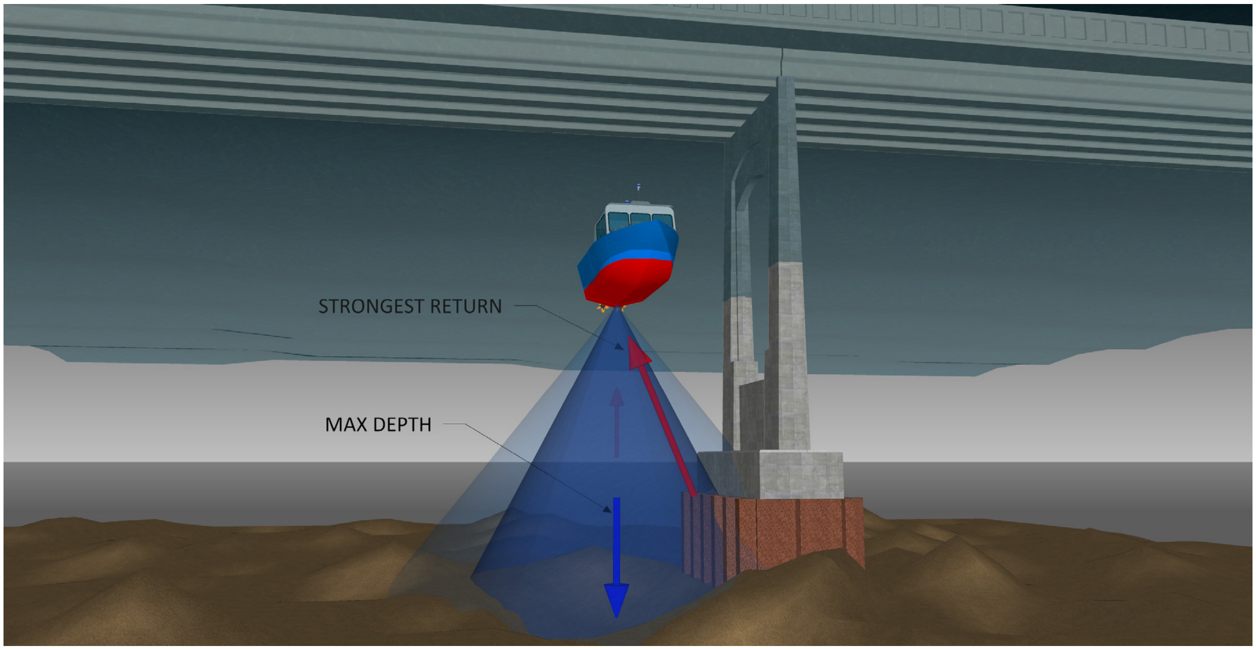

Figure 8. Example of a false sonar echo return near a bridge pier.

More advanced fathometer systems are compatible with GPS receivers or robotic total stations and allow geographic coordinates to be associated with each depth reading. When a fathometer is coupled with one of these devices, water depths can be post-processed and referenced to a state plane or other horizontal coordinate system. This allows for very accurate channel-bottom surveys, which can be easily compared to future surveys. When water conditions allow, a boat-mounted transducer allows efficient data collection. However, transducers mounted on poles, floats, or articulated arms have been used when maneuvering a boat is unfeasible due to high flows.[14]

A fathometer survey conducted during a typical underwater inspection for many of the state transportation agencies may include recording channel-bottom profiles along the bridge fascias, as well as 100 feet and 200 feet upstream and downstream of the bridge. However, other states obtain significantly more data for a complete hydrographic survey on certain waterways. Figure 9 illustrates a typical contour map of a bridge site showing scour around the piers. The figure was produced using single-beam sonar data.[14]

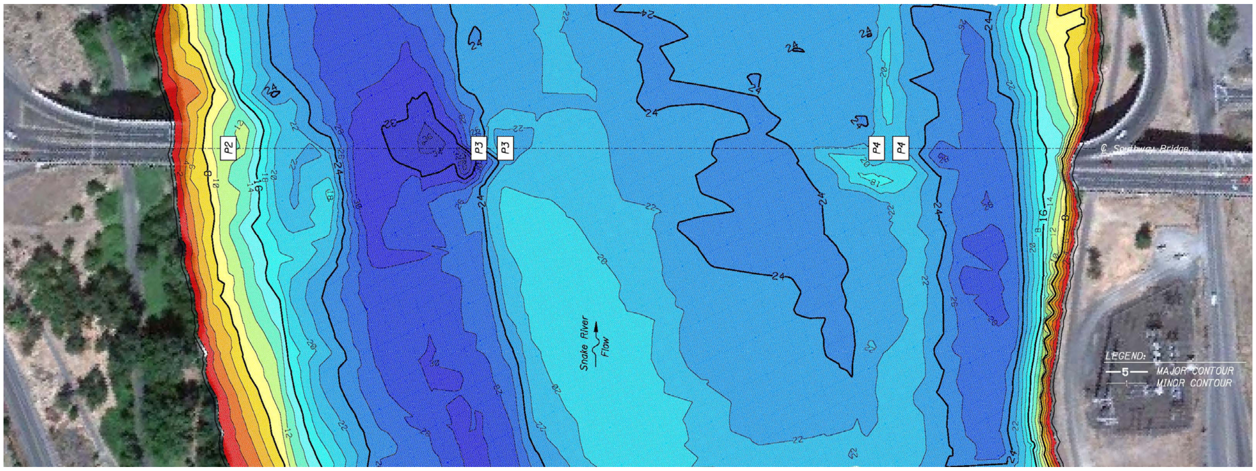

Figure 9. Typical single-beam hydrographic survey plan of a bridge site.

4.2.1.1 Advantages of Fathometers and Echosounders

The primary benefit of a fathometer is the ability to obtain geo-referenced channel-bottom profiles. The profiles can be used to locate and quantify apparent scour depressions, areas of infilling, and channel-bottom objects such as exposed pier footings or debris accumulation. Overlaying and comparing channel-bottom profiles from successive underwater bridge inspections can alert engineers to possible channel-related problems. Bridge foundation information from as-built plans can be superimposed onto the channel cross-sections and profiles for reference purposes.[15]

4.2.1.2 Limitations of Fathometers and Echosounders

The primary limitation of a fathometer is its inability to collect data outside the path of the vessel transporting the transducer. For this reason, the functionality of fathometers is limited to obtaining channel-bottom depth information only and imaging of vertical structure faces is not practical.[15]

Data density is typically low in comparison to data obtained by multi-beam sonar collection methods. For instance, a single-beam fathometer survey will typically cover only 5 to 10 percent of the total channel-bottom area.[12] This limitation prevents detection of channel-bottom irregularities or scour holes unless the vessel passes directly over the top of the interested area with a narrow beam. Additionally, contour maps created from single-beam sonar rely heavily on interpolation between data points. In other words, data obtained from these systems doesn't possess good enough resolution to detect small irregularities. For channel bottoms that are relatively flat, or that have a gentle slope, this method works well. Low data density and the presence of steep or irregular surfaces can cause data interpolation to show an inaccurate representation of actual conditions.

4.2.2 Geophysical Sub-Bottom Profilers

Sub-bottom profilers were first introduced in the mid-1960s and have been successfully used for defining sediment stratification and detecting bedrock for many years. The surface component of the system generates images of the sediment stratifications, bedrock, and objects embedded in the channel bottom using either a digital or paper recording device.[15]

The geophysical profiling systems can either be acoustic or electromagnetic radar. The electromagnetic radar system is referred to as Ground Penetrating Radar (GPR). Radar waves are different than sonar waves. Two acoustic sub-bottom profiling systems are the Tuned Transducer operating between 2-15 kHz and the Chirp Color Sonar operating between 200 Hz – 30 kHz.[15]

Scour is most prevalent during a flood event; however, hazardous site conditions including complex flow patterns and the presence of drift and debris frequently prevent personnel from safely positioning instruments or diving during these events. After a flood event, the waterway current decreases and sediment is typically deposited into the scour depression. As the deposited sediment will typically consist of a different material or have a different density than the true channel-bottom sediment, the sub-bottom profiler will depict the location of the previously undisturbed channel bottom. Sub-bottom profilers are also used to locate the position and depth of buried submarine cables below movable bridges prior to repair work or channel dredging operations.[15]

4.2.2.1 Advantages of Geophysical Sub-Bottom Profilers

The primary benefit of sub-bottom profilers is the ability to locate sediment stratifications, bedrock, and objects embedded in the channel bottom. As a result, sub-bottom profilers are frequently used prior to marine structure construction or as part of a scour evaluation to detect infilling of depressions. With regard to underwater bridge inspection, sub-bottom profilers can be used to measure the true depth of scour depressions and locate unknown elevations of embedded pier footings.[15]

4.2.2.2 Limitations of Geophysical Sub-Bottom Profilers

The primary limitation of sub-bottom profilers is acoustic interference, which results in sub-bottom images that are more difficult to interpret. Acoustic interferences include multipath when operating in shallow water. Additionally, because sub-bottom profilers use significantly lower operating frequencies than fathometers, the cone angles are typically much wider. As a result of these wider cone angles, collecting good quality sub-bottom images close to in-water structures is challenging. Side-lobe interference can occur when the acoustic pulses encounter vertical objects, such as a bridge pier.[15]

There are also several important limitations specifically for GPR used in waterways. GPR cannot currently be used in saline waters or at depths that are great than approximately 30 feet.[16]

4.2.3 Multi-Beam Swath Sonar

Multi-beam swath sonar was first developed by SeaBeam Instruments in the mid 1960's for the U.S. Navy. Multi-beam swath sonar consists of a line of numerous narrow circular beams. The beam arrangement allows detailed mapping of a very thin transverse section with each sonar pulse. Most systems are boat mounted and require forward progress of the boat to advance the position of the send/receive signal.[9] Operating frequencies usually range between 0.7 MHz and 1.8 MHz. Other multi-beam swath systems are setup with extremely low frequencies for sub-bottom profiling applications.[15]

Multi-beam sonar systems also referred to as swath echosounders, function similar to single-beam echo sounders except, they have multiple sonar beams acting simultaneously allowing for much more dense data coverage in a shorter period of time. This type of system uses a fanned array of sound beams that typically give near 100 percent coverage of the seafloor or channel bottom. For instance, a typical multi-beam survey may have a fanned array that is capable of a "swath width" of seven times the water depth. This means that if the water is 100 ft deep, bathymetric data can be obtained up to a swath of 700 ft wide, or 350 ft to the port or starboard side of the survey vessel. For vertical imaging applications, the same theory applies but the swath width is dependent upon the distance between the transducer and the pier face. Since the direction and angle of the beams can change with the heave, pitch, and roll of the survey vessel, it is necessary to have motion compensators and a gyrocompass that account (in real-time) for the motion and relay correction factors back to the on-board processor.[14]

Another form of multi-beam sonar is three-dimensional mechanical scanning sonar, which is essentially a multi-beam sonar unit fitted with a mechanical stepping motor. The sonar needs to remain stationary while performing scans.

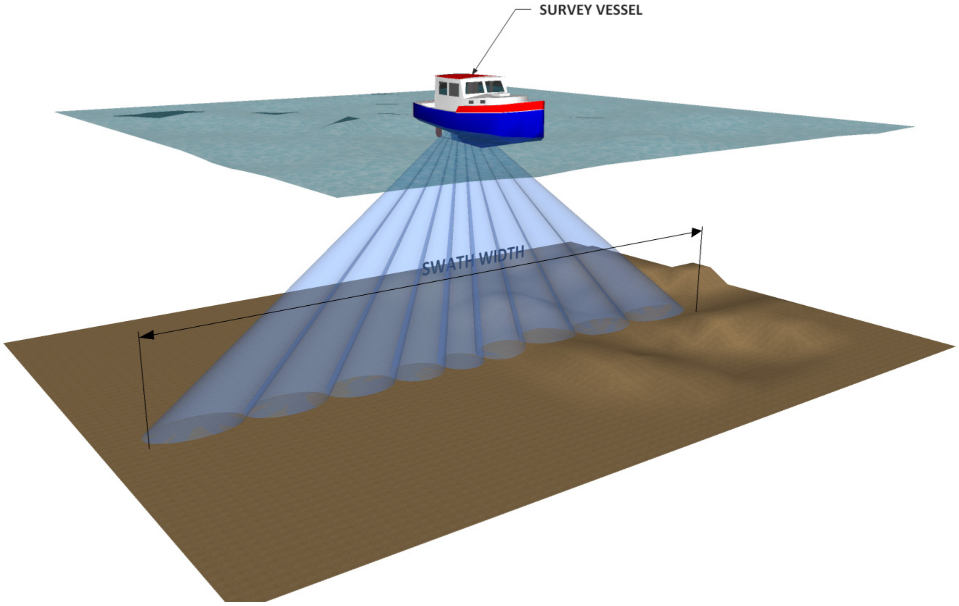

Figure 10. Multi-beam swath sonar beam pattern.

4.2.3.1 Advantages of Multi-Beam Swath Sonar

The primary benefit of multi-beam swath sonar is the ability to quickly obtain large quantities of three-dimensional data. Multi-beam swath sonar produces a three-dimensional still image that is often referred to as a point cloud. For bridge inspection applications, the production of three-dimensional data would allow an inspector to document and assess the depth of spalling, scaling, or possibly even foundation undermining. By using multiple or overlapping passes, the sonar operator is able to obtain greater data density and 100 percent bottom coverage of the area.[14]

4.2.3.2 Limitations of Multi-Beam Swath Sonar

The primary limitations of multi-beam swath sonar are that the vast quantities of data produced can be cumbersome and time consuming to post process. Because of the additional sensors required and the complexity of the relationship between these sensors, a temporary multi-beam installation is significantly more complex and time consuming than a comparable single-beam installation.[12] Both field operation and data post processing require a greater deal of training and skill to master than sector scanning imaging sonar used without motion compensation or GPS positioning. Additionally, multi-beam sonar systems are considerably more expensive than other products.

The final limitation of multi-beam sonar as it pertains to bridge inspection is the difficulty of such systems to smoothly transition from acquiring data from the channel to the vertical face of a bridge support when they are in a downward looking configuration. This occurs because multi-beam systems are finely tuned through power and gain adjustments to detect the channel bottom and thus don’t always accurately record returns from dissimilar materials and locations. Additionally, the data often requires a large amount of manual post processing to weed out the acoustic noise. In the hands of a skilled technician multi-beam swath sonar can yield high quality surveys but the relative complexity compared to single-beam systems is a definite barrier to entry. It should also be noted that multi-beam systems would be a poor choice for shallow waterways with relatively simple bottom topography. However, in areas with certain environmental characteristics (e.g., deeper water, complex bottom topography, limited visibility, strong currents, etc.) multi-beam surveying offers a number of unique benefits relative to any other existing technologies.[12]

4.2.4 Real-Time Multi-Beam Sonar

Real-time multi-beam sonar is a modified version of multi-beam swath sonar. Instead of using a single line of narrow beams, it contains many rows and columns of narrow beams that ensonify a volume, allowing for more dense data coverage. For example, thousands of data points are created with a single ping as opposed to hundreds with traditional swath multi-beam systems. These systems create three-dimensional images that are updated in real-time, similar to watching a video and they can be mounted on a vessel, ROV/AUV or fixed installation. Figure 11 illustrates the beam pattern of a typical real-time multi-beam sonar system.

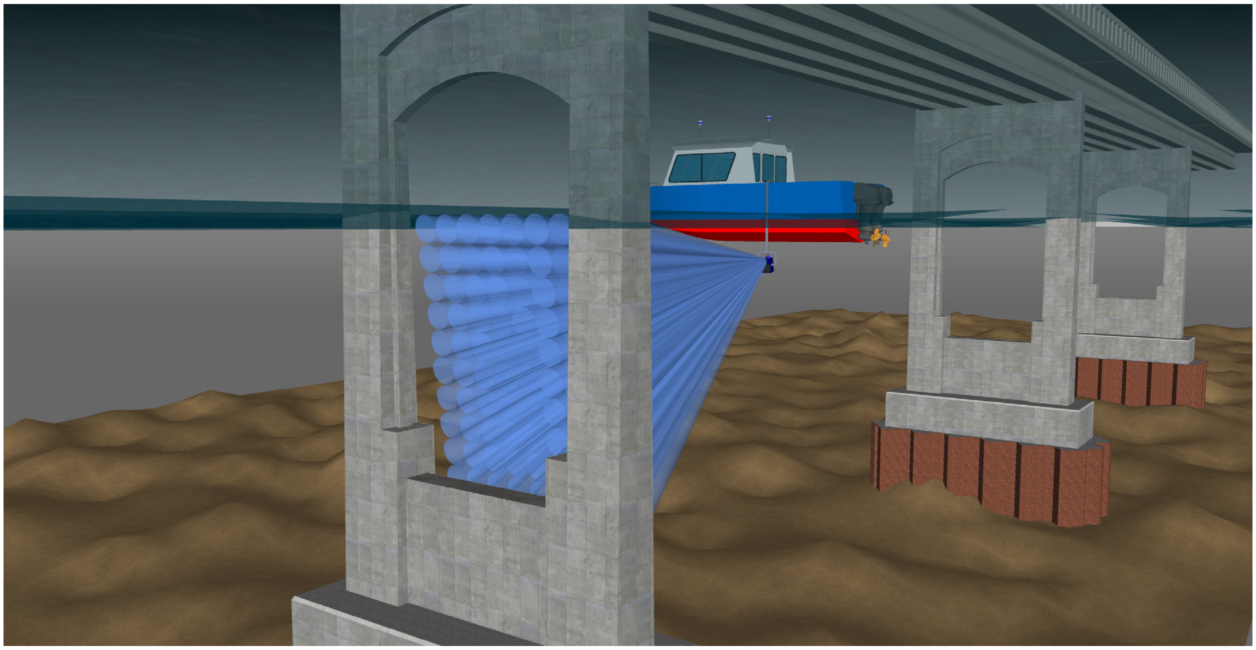

Figure 11. Real-time multi-beam sonar beam pattern.

4.2.4.1 Advantages of Real-Time Multi-Beam sonar

There are many advantages when using real-time multi-beam sonar systems. Real-time multi-beam sonar provides the benefits of 3-D data but unlike traditional multi-beam systems, some can be rapidly deployed and require less special operator skills, training, and post processing. Due to the large number of beams and high data density, large and complex structures can be covered quickly without the need for multiple passes. The end result is greatly increased productivity.[17]

Because a single geo-referenced point on an object being scanned is continuously ensonified from different angles as the platform moves, multipath error can be reduced by software algorithms that track whether objects remain stationary between consecutive pings. This produces datasets with less acoustic noise. Another advantage to continuously scanning each object from multiple angles is that the dataset produced has less acoustic shadows resulting in fewer unknowns from the dataset. [18]

4.2.4.2 Limitations of Real-Time Multi-Beam sonar

Real-time multi-beam sonar systems have the same limitations as swath multi-beam. Another limitation is that although real-time multi-beam sonar systems can be used as a “stand alone” unit, they still need to be fully geo-referenced using GPS and motion compensating devices for the best results. This adds an extra level of cost to already expensive systems and creates more equipment to maintain.

4.3 TWO-DIMENSIONAL IMAGING SONAR

4.3.1 General

Two-dimensional imaging sonar systems have oblong, fan-shaped beams. They essentially work by recording the full range of returns from the wide dimension of the cone angle and plotting them on a two-dimensional drawing. The sonar unit can't distinguish which portion of the wide cone angle a return came from but it can tell if an echo returns from more than one distance. Figures 12, 13, and 14 illustrate the orientation of sector scanning sonar's fan beam to produce a plan view image; a section cut image, and an elevation view of the pier face respectively. The same beam orientations are used to produce similar images with other two-dimensional sonar such as side scan sonar and lens-based multi-beam sonar.

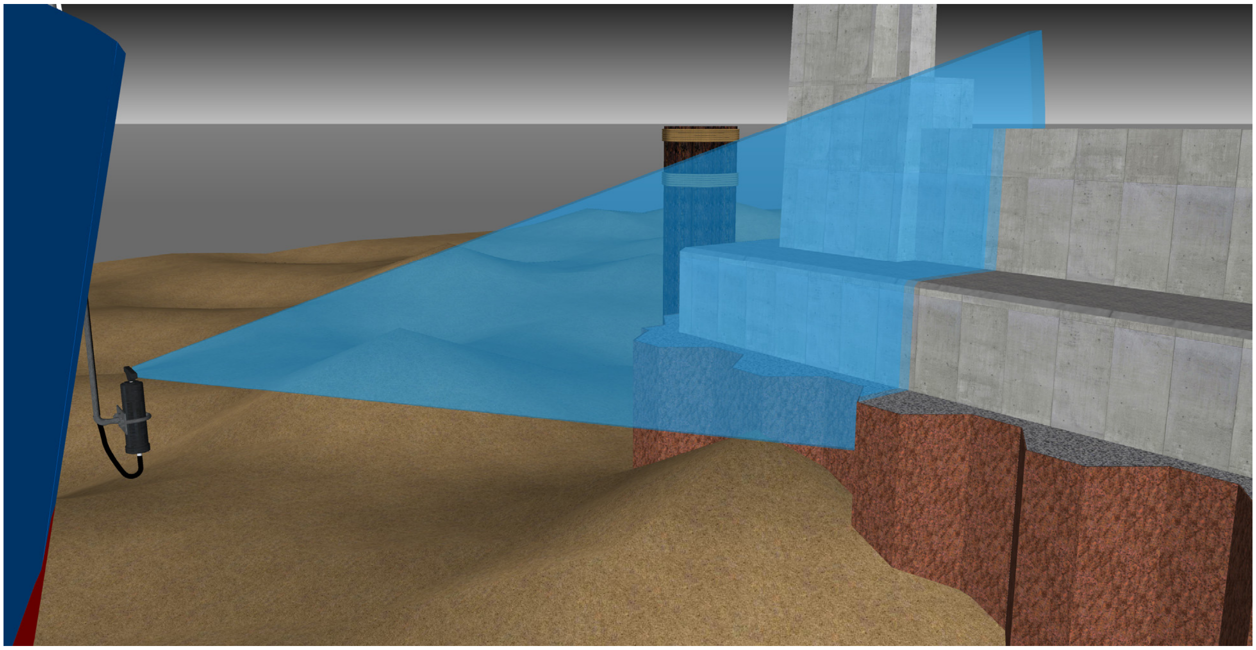

Figure 12. Orientation of fan beam to produce a plan view image.

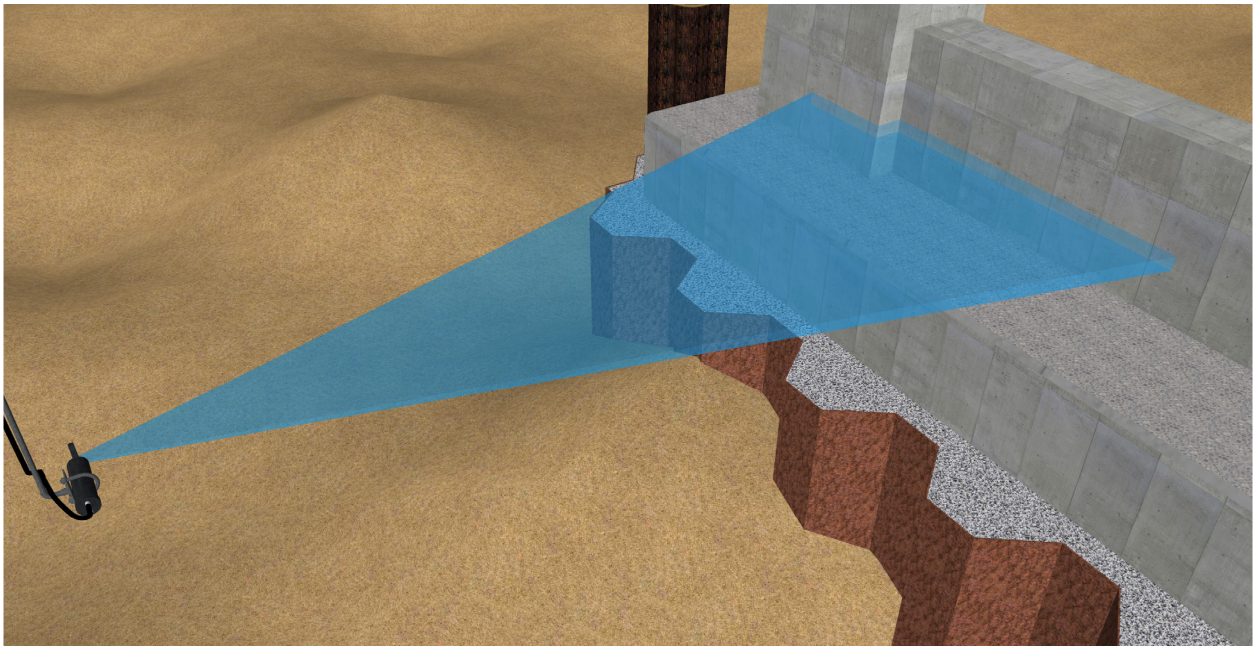

Figure 13. Orientation of fan beam to produce a section cut image.

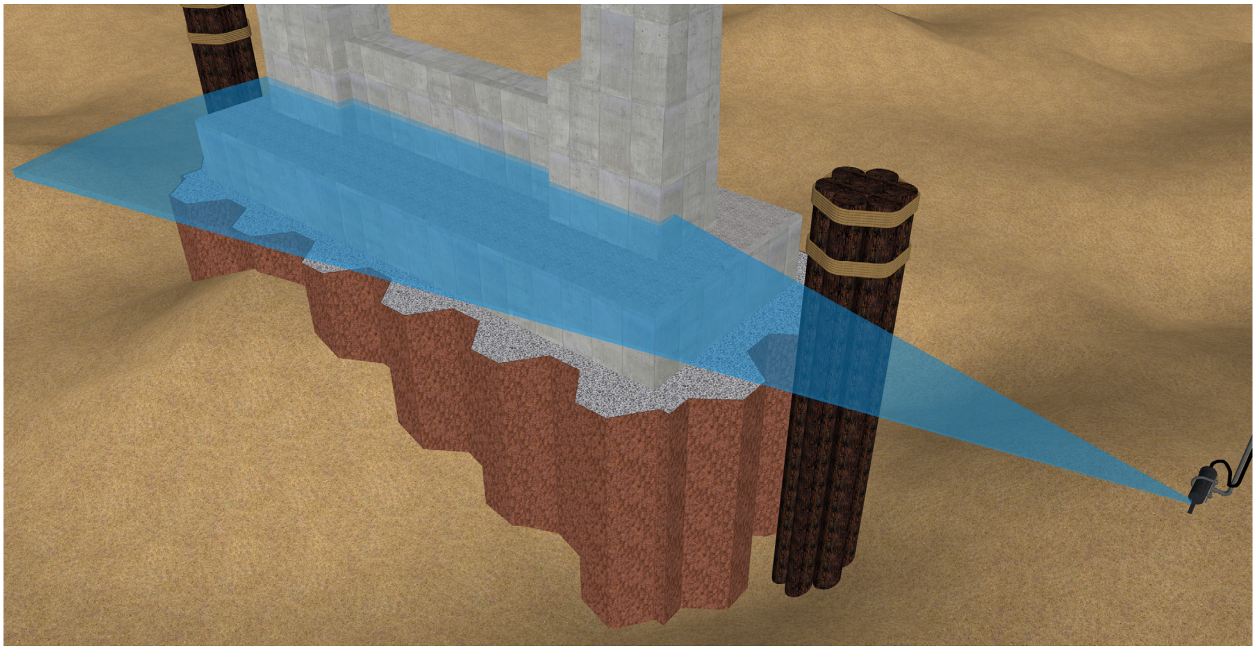

Figure 14. Orientation of fan beam to produce an elevation view image.

4.3.1 Side-Scan Sonar

Side-scan sonar was first introduced in the early 1960s and has been successfully used for documenting underwater findings for many years. Side-scan sonar operating frequencies usually range between 83 kHz and 800 kHz. Side-scan sonar works by emitting fan-shaped acoustic pulses through the water column. The beam is narrow in one plane (typically less than 1°) and wide in the other plane (typically between 35° and 60°). Figure 15 shows the shape of a typical side-scan sonar beam and step spacing. The transducer is either towed behind a boat or mounted on the transom or hull of the vessel. Side-scan sonar requires the boat to have forward progress so each successive sonar ping will be positioned slightly in front of the previous. The resulting images from the channel bottom and objects located on the bottom or in the water column are representative of the echoed (backscattered) target intensity within the geometric coverage of the beam. When the images are stitched together along the direction of travel, they form a contiguous image of the bottom and objects located on the bottom or in the water column.[15]

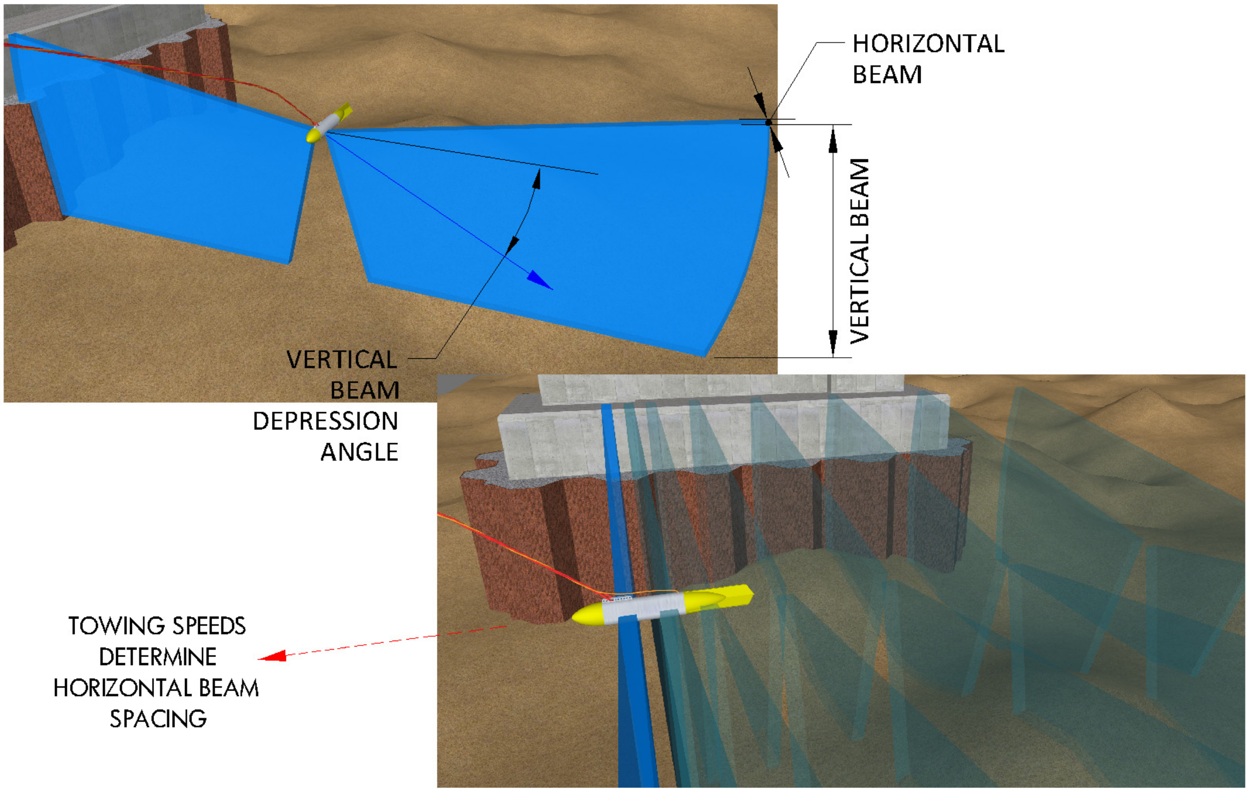

Figure 15. Side-scan sonar beam shape and step pattern.

4.3.1.1 Advantages of Side-scan sonar

The primary benefit of side-scan sonar is the ability to quickly and efficiently generate images of large areas of the channel bottom. For this reason, side-scan sonar is considered the tool of choice for large-scale search operations. Side-scan sonar can be used for many purposes, including delineation of exposed sediment and geologic formations, detection of underwater debris or objects that may be hazardous to marine operations and searching for shipwrecks. In addition, the general location and configuration of submerged structures, pipelines, and cables can be investigated using side-scan sonar.[11]

4.3.1.2 Limitations of Side-scan sonar

The primary limitation of side-scan sonar is the inability to generate images of the vertical components of submerged structures. It is possible to image vertical components of bridge substructures with side-scan sonar; however, the transducers must be rotated 90 degrees and pole-mounted. The quality of the image that results is largely dependent on the operator's ability to maintain a close and constant distance to the pier face and maintain a constant speed while driving the boat past the bridge pier.[11] Figure 16 demonstrates the beam pattern that a side-scan sonar produces when being utilized in the traditional configuration and when rotated 90° for imaging of vertical surfaces.

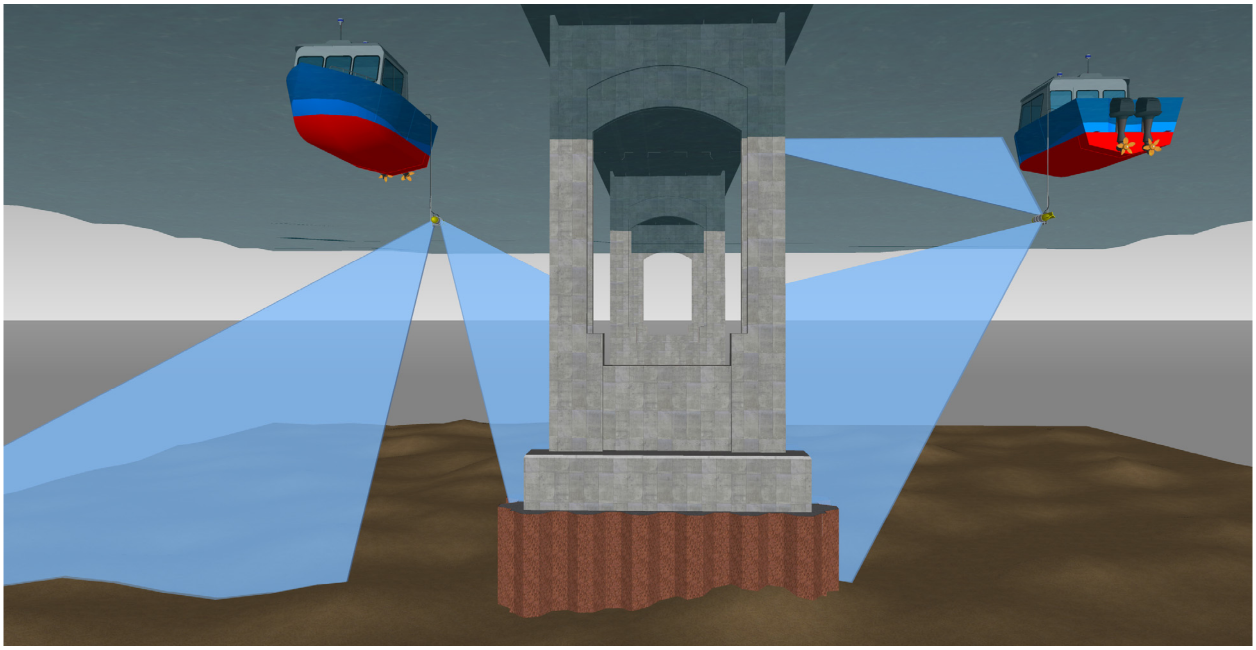

Figure 16. Side-scan sonar mounting positions for structural imaging (right) and bottom scanning (left).

As a result, sector-scanning or multi-beam sonar are generally considered better solutions for generating images of the vertical components of submerged structures. Other limitations to side-scan sonar include: the inability to maintain step size and thus detect narrow linear targets parallel to the beams; difficulty keeping the towfish at a constant location behind the vessel and at a constant elevation in the water column; keeping the vessel along a consistent line at a constant speed; and vessel pitch and roll, especially if using a hull-mounted application.[14]

4.3.2 Sector-Scanning Sonar

The first known use of sector-scanning sonar for a bridge assessment was to investigate the location and resting position of a sunken pontoon bridge deck for the Washington DOT in the early 1990's. Although scanning sonar was used to investigate submerged structures more than

20 years ago, it was not until circa 2000 that higher resolution imaging devices became readily available at cost effective prices. Since 2000, numerous bridges have been scanned to document underwater conditions.[14]

Scanning sonar works similarly to side-scan sonar in that the transducer emits fan-shaped acoustic pulses through the water; however, unlike side-scan sonar, which requires vessel movement to develop an image, scanning sonar works best if the transducer remains stationary while the head is mechanically rotating. The acoustic images are recorded in a series of "slices" generated by a ping after each rotation of the transducer. Scanning sonar operating frequencies usually range between 330 kHz and 2.25 MHz, with a common frequency used for channel bottom and structural imaging of 675 kHz.[14] Figure 17 shows the fan-shaped beam and scanning pattern produced by typical sector-scanning sonar.

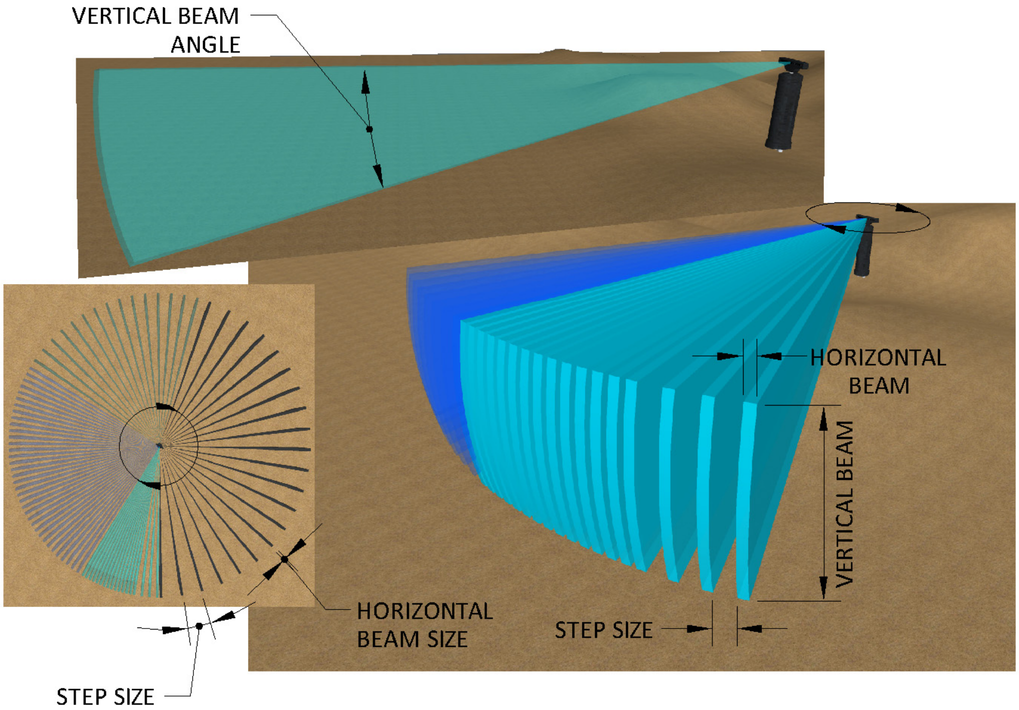

Figure 17. Sector-scanning sonar beam shape and step pattern.

4.3.2.1 Advantages of Sector-Scanning Sonar

The primary benefit of scanning sonar is the ability to produce detailed images of the channel bottom and vertical components of submerged structures that extend from the channel bottom to the water surface. Scanning sonar can also be used prior to and during diving operations to direct the underwater inspector to potential deficiencies, as well as direct the inspector around potential below-water hazards.[14] Sector scanning of vertical structure surfaces typically does not require geo-referencing thus simplifying the process.

4.3.2.2 Limitations of Sector-Scanning Sonar

Due to limited range and the need for the sonar head to be located in a stable mounting position, the primary limitation of scanning sonar is that stationary setups require greater time to obtain. Additionally, developing highly detailed images using scanning sonar is heavily dependent on sonar positioning and stability.[14]

4.3.3 Lens-Based Multi-Beam Sonar

In the late 1990s, the U.S. Navy funded the development of lens-based multi-beam sonar at the University of Washington Applied Physics Laboratory to identify swimmer intruders. It was not until around 2004 that the offshore oil and gas industry began using lens-based multi-beam sonar for structural inspection and for navigation with ROV's.[14]

Lens-based multi-beam sonar is essentially scanning sonar that does not rotate. Where scanning sonar consists of one beam that mechanically moves each transmit/receive cycle to create an image line by line, lens-based multi-beam sonar consists of numerous elliptical beams placed side by side to create an image in one transmit/receive cycle. Operating frequencies typically range between 0.7 MHz and 1.8 MHz.[14]

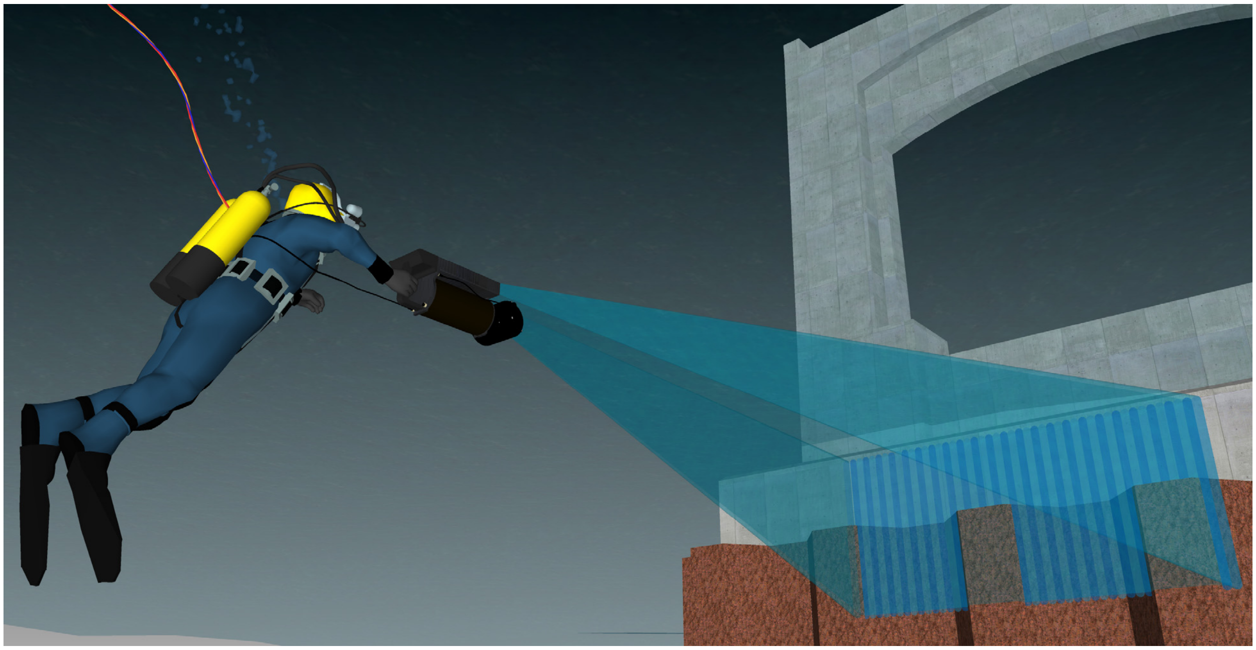

Figure 18. Lens-based multi-beam sonar beam pattern.

4.3.3.1 Advantages of Lens-Based Multi-Beam Sonar

The primary benefit of lens-based multi-beam sonar is that it provides real-time images, similar to a video, as opposed to photo-like stills produced with scanning sonar. In addition, battery operated units with a mask-mounted display can be carried by an underwater inspector. Using a diver carried unit, an underwater inspector can navigate to potential deficiencies as well as around potential below-water hazards.[14] Because lens-based multi-beam sonar displays images in real-time, they show promise for use in tracking or directing a dive inspector and are not as sensitive to movement of the transducer head.

4.3.3.1 Limitations of Lens-Based Multi-Beam Sonar

The primary limitations of lens-based multi-beam sonar units are the difficulty in obtaining complete images of vertical surfaces. Additionally, because the image produced is two-dimensional, obtaining depth of scaling or undermining penetration information is not possible.[14]

5.0 RELIABILITY OF SONAR DATA

5.1 GENERAL

FHWA Technical Advisory 5140.21 states that “underwater members must be inspected to the extent necessary to determine structural safety with certainty”. However, the reliability of above water and underwater data collection is subject to a number of factors including the inspector’s skill and the parameters of the inspection equipment operation. This section will focus on several locations for possible errors in the collection and interpretation of sonar data. This research study encompasses sonar use to obtain information about submerged substructure surfaces and the adjacent channel bottom surface. While there is very little literature available on acoustic imaging submerged vertical surfaces, there is a tremendous amount of information published on using sonar for water depth measurements to the channel bottom. In fact, government-funded dredging projects utilize sonar data for environmental planning, accurate progress measurement, and final contractor payment of work completed. Therefore, the reliability of interpreted water depth sonar data has been studied for years. Fortunately, the principles related to the reliability of sonar data for underwater acoustic imaging of submerged bridge substructure surfaces are very similar.

The inherent errors and methods associated with correcting single-beam and multi-beam sonar data has been well documented in the hydrographic survey industry. For a detailed reference on hydrographic surveying, readers are referred to the USACE Engineering Manual (EM) 1110-2-1003, “Hydrographic Surveying”.[13] Additionally, the USACE Hydrographic Surveying EM is heavily referenced throughout this chapter.

5.2 CALIBRATION OF SONAR EQUIPMENT

Because the speed at which sound travels through water is not constant throughout the depth of a typical water column, calibration of sonar equipment to local conditions is necessary for accurate data recording. The two primary methods for respectively measuring and correcting for variances in sound velocity through the water column are the bar check and the sound velocity probe.[13]

The bar check is a procedure that measures the distance to an object set at a known depth and adjusts for the actual speed of sound to correct any inaccuracies. This effort is usually completed by lowering a metal disk suspended by a chain into the water. This method corrects the depth readings based on an assumed average velocity. It should be noted that the bar check does not correct the sound velocity along the full depth of the water column, nor does it generate the necessary information to make corrections for sound refraction as it passes through layers of water with varying properties.[13]

Alternatively, a sound velocity probe may be lowered through the water column. This technique uses an instrument that measures sound velocity at each point throughout the full height of a water column. With the input of this data, a sonar system’s software will either apply an average velocity over the entire column, or the velocities will be continuously corrected at each depth throughout the water column.[13]

5.3 TRANSDUCER HEAD MOVEMENT

Production of high quality sonar data requires that the exact position and orientation of the transducer head be known at all times. If a transducer head is fixed in a stationary position (i.e., set in a tri-pod on the channel bottom), this criterion is met. If the transducer head is mounted to a boat, the effects of waves, current, and other boat movements will greatly affect the resulting sonar data unless accurate correction factors are applied.[13]

Movements of a typical boat-mounted transducer can be classified into the categories of roll, pitch, yaw, and heave as illustrated in Figure 19 below. Roll is defined as rocking of the boat from side to side. Pitch is defined as rocking of the boat from front to back. Yaw is defined as the change of compass orientation of the vessel. Finally, heave is defined as the up and down movement of a boat, usually produced by waves.[13]

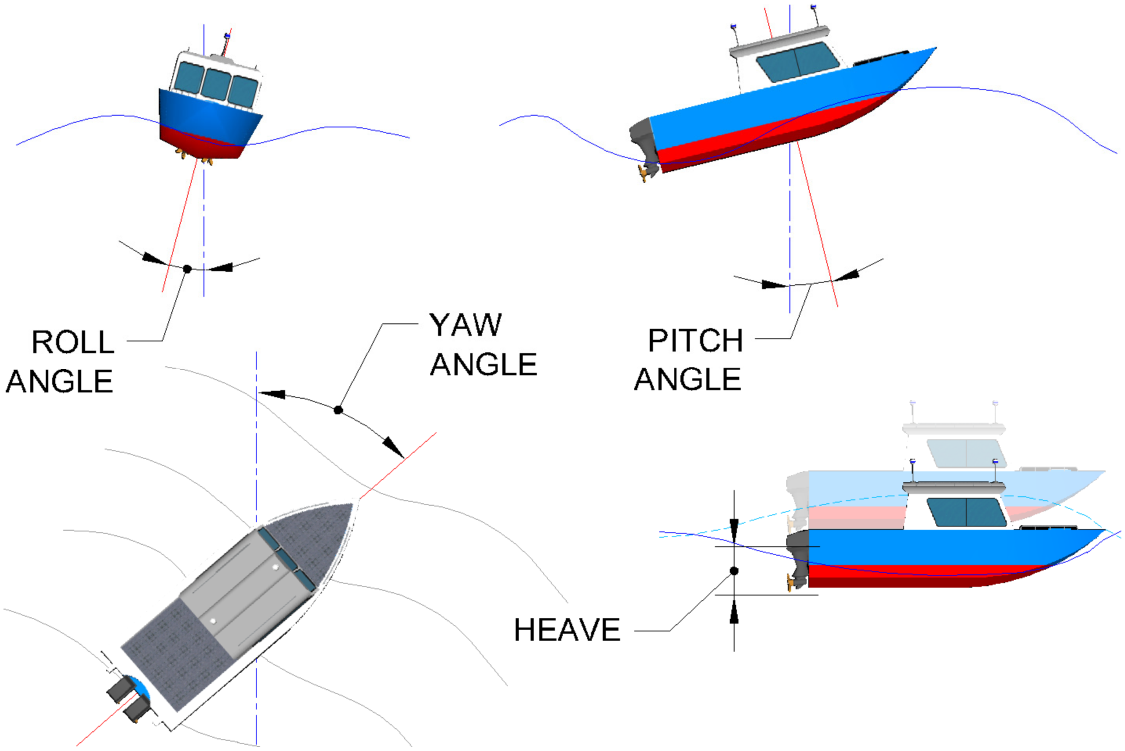

Figure 19. Graphic depictions of roll, pitch, yaw, and heave.

The effects of the above movements can all be accurately calculated and corrected with commercially available motion compensation equipment; however, not all sonar systems accept motion compensation signals from these devices.[13]

5.4 INTERFERENCE AND NOISE

The time length of each transducer ping is called the pulse length. The bandwidth is a term that refers to the range of frequencies that a sonar receiver can hear in the return echo. The bandwidth is typically set to accept a range of frequencies from slightly above to slightly below the transducer's transmitted frequency. Optimum high-resolution imaging conditions require a short pulse length and a wide receiver bandwidth. However, if the bandwidth is set too high, the system becomes susceptible to background noise from outside sources such as ship motors, other sonar systems in the area, rain, waves, whales or other mammals, pile driving, and vibrations from traffic passing over a bridge deck. Ideally, a sonar system's software should allow the user to turn off the transmit cycle to the system and allow the operator to listen for any noise in the area.[11]

Some imaging sonar systems are equipped with a variable bandwidth setting. The combination of these two functions allow a sonar operator to listen to and map local background noise, then select an operating frequency and bandwidth that will produce the highest resolution images with the least interference.[11]

5.5 ACOUSTIC MULTIPATH

Acoustic multipath is terminology that refers to a sonar echo event bouncing off of multiple objects prior to returning to the transducer. This phenomenon can occur when scatter from the return echo bounces off of the water surface, thermocline or other object, and is then directed back to the target before returning to the transducer. The sonar receiver is not able to distinguish that the sound did not take a direct route to the target and back, and therefore it is typically displayed as multiple targets at incremental distances from the transducer when only one target exists in reality. Acoustic multipath becomes an increasingly common problem when working in relatively shallower water depths, which are typically at bridge sites.[11]

Acoustic multipath can usually be eliminated by[11]:

- Selecting a shorter operating range.
- Changing the transducer height in the water column.
- Tilting the transducer away from the water surface.
- Using a transducer with a narrow beam.

5.6 GEOMETRIC LIMITATIONS

Resolution of a sonar system refers to its ability to accurately display small objects. The resolution is dependent on many factors including frequency, bandwidth, pulse length, target reflectivity, and monitor pixel size. Resolution is different in the transverse and longitudinal directions and both resolutions are commonly reported by manufacturers. An understanding of resolution is critical to understanding the limitations of images produced by sonar.[11] For the resolution calculations listed below, the resolution value can be thought of as the image pixel size that the sonar is capable of defining. A lower resolution value means a better picture.

5.6.1 Transverse Resolution

Transverse resolution refers to a sonar system's ability to resolve small target images in the direction perpendicular to the sonar beam and is primarily dependent upon the sonar cone angle and the distance from the transducer to the target being imaged. With theta being defined as two times the cone angle, the footprint of a sonar beam can be easily calculated using basic trigonometry as shown in Figure 20.

$$Transverse\ Footprint\ = 2 \times distance \times (tangent\ [\theta/2])$$

Figure 20. Equation for calculating transverse resolution.

When viewing a sonar image, if two targets fall within the footprint of the sonar cone, the sonar will not be capable of distinguishing between them. It is also important to understand that the calculations for resolution in Table 5 are based upon optimum conditions of frequency, bandwidth, target reflectivity and monitor pixel size. The resolution can never be better than stated in Table 5 below, but it can be worse. [11]

Table 5. Effect of cone angle and distance on transverse resolution.

Sonar Transverse Cone Angle	Footprint @ 5 ft from Sonar head	Footprint @ 10 ft from Sonar head	Footprint @ 20 ft from Sonar head	Footprint @ 50 ft from Sonar head	Footprint @ 100 ft from Sonar head
0.3°	0.3 in.	0.6 in.	1.2 in.	3.1 in.	6.3 in.
0.5°	0.5 in.	1.0 in.	2.1 in.	5.2 in.	10.5 in.
1.0°	1.0 in.	2.1 in.	4.2 in.	10.5 in.	20.9 in.
1.7°	1.8 in.	3.6 in.	7.1 in.	17.8 in.	35.6 in.
2.0°	2.1 in.	4.2 in.	8.4 in.	20.9 in.	41.9 in.

Transverse resolution can additionally be affected by step size. For scanning sonar, this term refers to the distance that the sonar head is rotated with each mechanical advancement. For side-scan or multi-beam sonar, this terminology is typically dependent upon the speed at which the boat is moving. For practical purposes, if the step size exceeds the footprint of the sonar beam, full coverage of the surface being imaged will not be obtained. This reliability issue relating to resolution can typically be avoided by scanning at slow speeds.[11]

5.6.2 Range Resolution

Range resolution refers to a sonar systems ability to resolve small target images in the direction parallel to the sonar beam, and it is primarily dependent upon the sonar pulse length and the speed of sound through the water.

$$Range\ Resolution = Pulse\ Length\ \times \frac{Speed\ of\ Sound}{2}$$

Figure 21. Equation for calculating range resolution.

When viewing a sonar image, if two targets fall within this distance to each other, the sonar will not be capable of distinguishing between them.[11] Most sonar systems automatically apply the sonar pulse length based on the selected range without allowing the user to manually adjust. If pulse length is manually applied, it is important to note that simply selecting a longer range will decrease resolution regardless of the distance to the target. If a sonar system allows manual selection of pulse length, the operator can select a shorter pulse length to achieve better resolution or a longer pulse length to achieve longer range.[11]

As an example to illustrate how range resolution is affected by pulse length, Table 6 illustrates the pulse length that a Kongsberg Mesotech 1071 scanning sonar manually selects for a defined range and the effect that it has on range resolution assuming a constant speed of sound equal to 4700 fps.

Table 6. Effect of range setting on range resolution.

Selected Range (ft)	Pulse Length (μs)	Range Resolution (in.)
15	25	1.4
75	28	1.6
150	85	4.8
300	114	6.4

5.7 ACOUSTIC SHADOWS

Another characteristic of sonar images is the formation of acoustic shadows. Shadows can easily be mis-interpreted as defects in a bridge substructure. Shadows appear as a dark spot on an image and are formed when a target blocks sound from reflecting off of that area of the surface. Shadows can look very similar in appearance to areas with extremely low reflectivity with the only revealing factor often being whether or not a target is shown at the leading edge. Depending on the angle of incidence, a sonar operator can often tell more about a target by its shadow than the actual sonar return.[11]

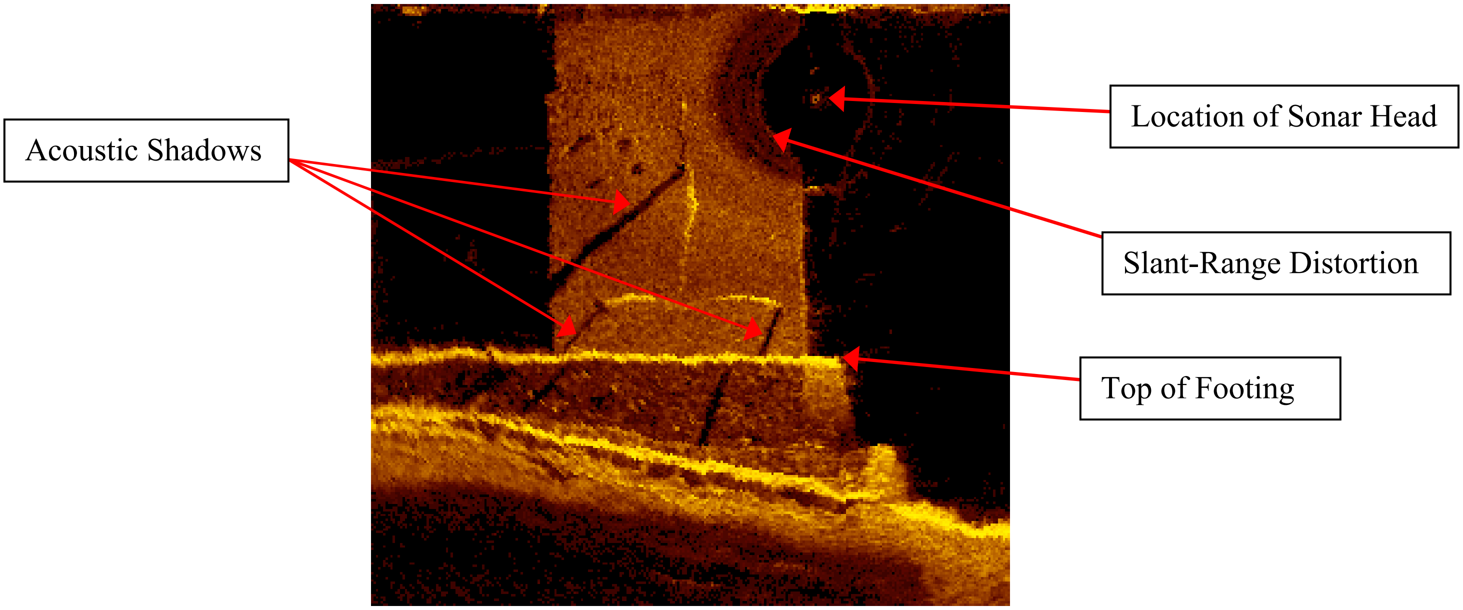

Figure 22. Sector-scanning sonar image with shadows on the face of a concrete pier.

By examining Figure 22, we can see what appears to be an inverted T-shape laying flat against the face of the concrete pier. A review of the bridge plans in Figure 23 reveals that the inverted T-shape is actually a steel frame designed to mount a fixed scour monitoring device to the pier and that it extends outward approximately 12 feet from the face of the pier. A bridge inspector unfamiliar with sonar may mis-interpret the submerged existing conditions shown in Figure 22 as concrete deterioration or cracking. Hence the need for sonar training and verification of "areas of interest" by qualified divers. The acoustic shadows cast against the face of the concrete in Figure 22 reveal that the object has depth in and out of the page. The acoustic shadow connects to the target that formed it at the location where the steel frame is connected pier face.

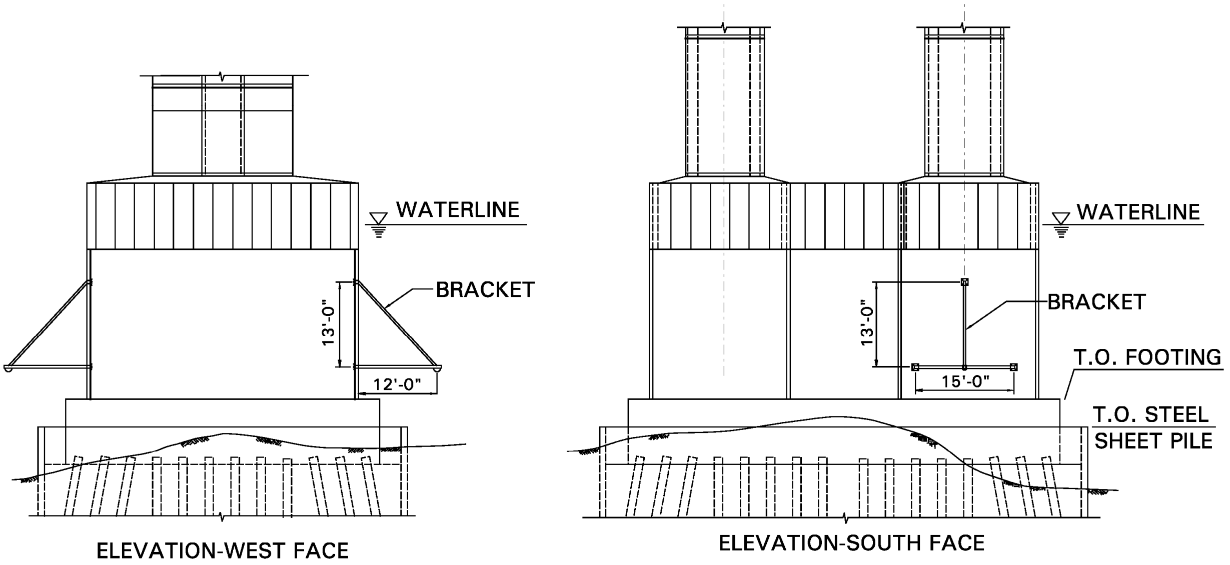

Figure 23. Fixed scour monitor system shown in sector scan image of Figure 22.

5.8 SLANT-RANGE DISTORTION

Most two-dimensional imaging sonar systems such as side-scan sonar, sector-scanning sonar, and lens-based multi-beam sonar have oblong, fan-shaped beams. They essentially work by recording the full range of returns from the wide dimension of the cone angle and plotting them on a two-dimensional drawing. Because the sonar unit can't distinguish which portion of the wide cone angle a return came from, a distortion error (referred to as slant-range distortion) is produced. Targets at the centerline of the beam are resolved at the correct distance but targets near either edge of the beam are plotted with respect to their echoed range. Refer to Figure 24 for a graphic illustration of echoed range versus actual range. Slant-range distortion is visually depicted by a concave or curved surface and is most pronounced near the sonar head.[11] The effects of slant-range distortion can be seen near the location of the sonar head in Figure 24.

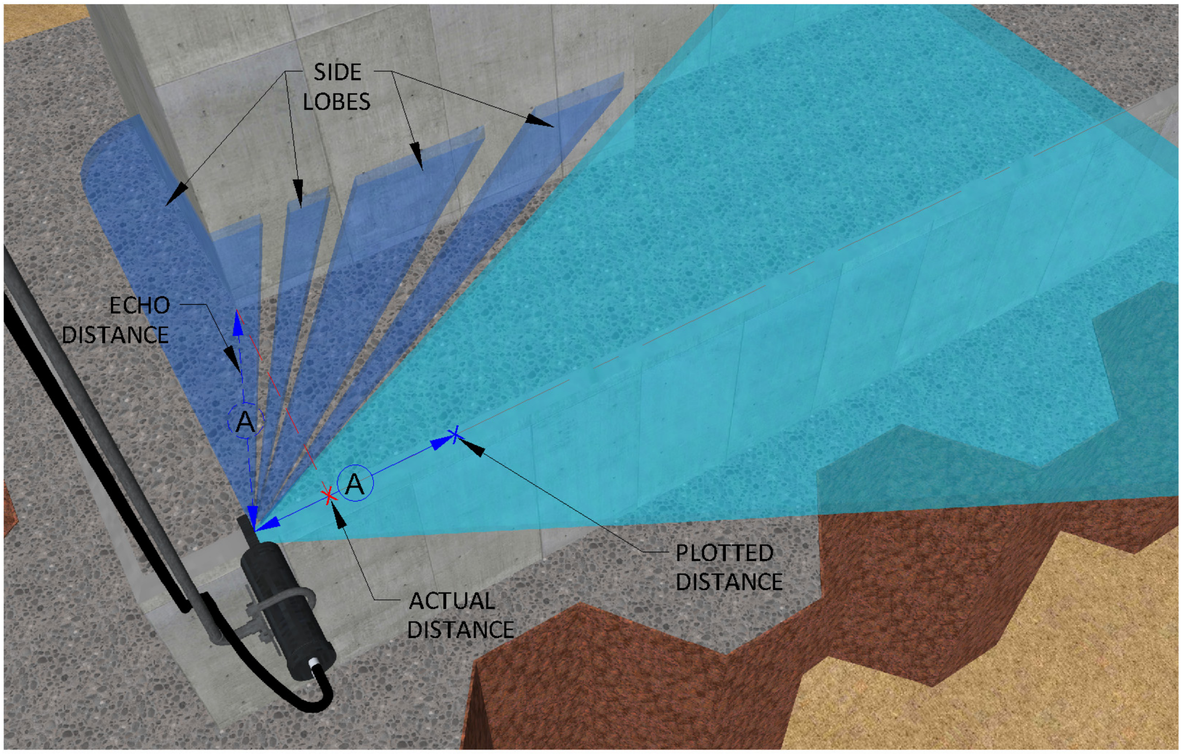

Figure 24. Echoed range vs. plotted distance of a sector-scanning sonar.

While slant-range distortion does continue throughout the full range of the beam, it is worst near to the sonar head and can be compounded by the effects of side lobes providing false readings. Slant-range distortion can be calculated based on the difference between the lateral and diagonal distance to a point on the structure being imaged. Thus, the distance at which the sonar head is held from the surface being imaged also effects slant range by increasing the angle to the target surface.[11] Therefore, it is useful to document the imaging stand-off distance used at a bridge site. Assuming a sector scanning transducer is held 5 ft from the face of a bridge pier, the slant-range distortion as a function of distance from the transducer head is illustrated in Figure 25.

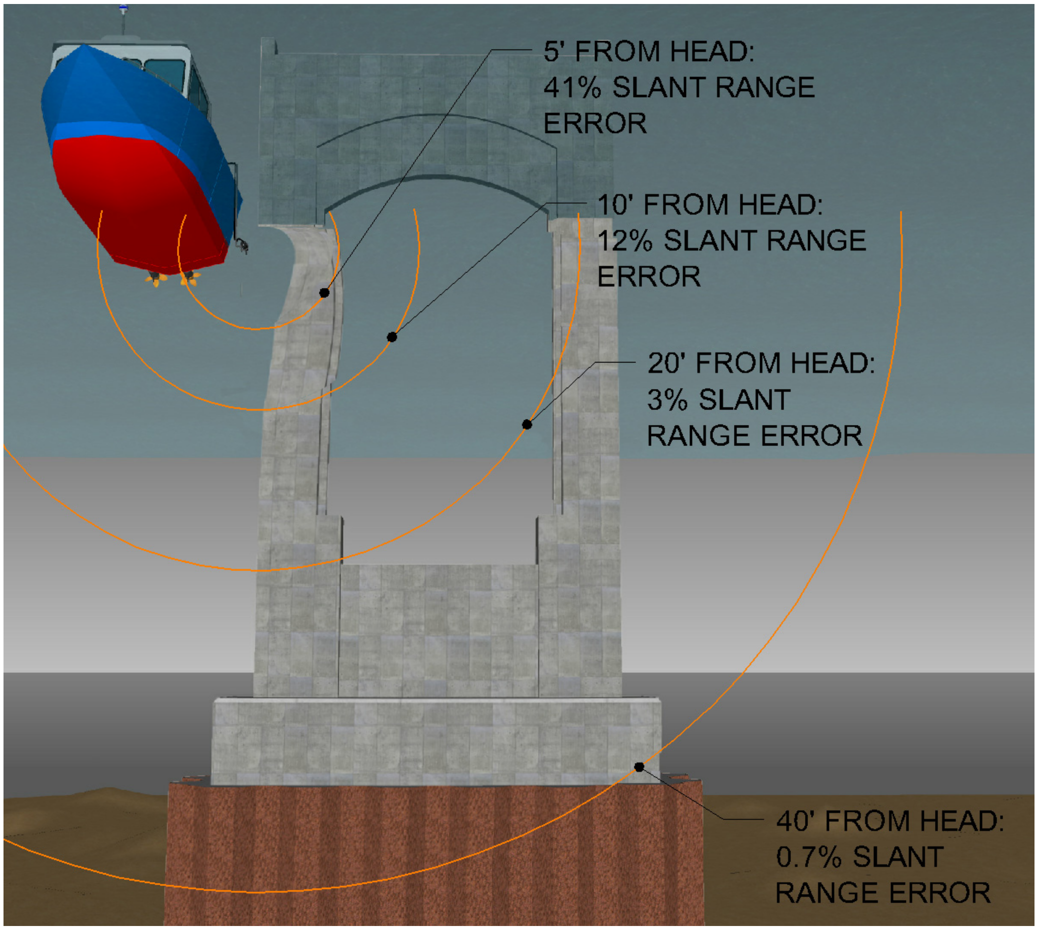

Figure 25. Slant-range distortion vs. distance from sonar head for sector-scanning sonar.

To help reduce the effects of slant-range distortion, the sonar head should be positioned a sufficient distance away from a target to reduce the effects. Another method of visually minimizing the affects of slant-range distortion is to remove heavily affected areas during image mosaic post processing. Additionally, some scanning sonar software has a built-in function that attempts to correct slant-range distortions.[11]

5.9 ACCURACY OF GPS

Besides the underwater acoustic properties previously discussed in Section 4, data reliability also deals with geo-referencing the obtained sonar points. It is important to note that multi-beam point cloud surveys and two-dimensional scanning sonar can both be used with or without using Global Positioning Systems (GPS) or motion compensation. However, geo-referencing the data ensures repeatability for future inspection comparison. One of the main limitations of typical multi-beam bridge surveys however, is that almost all high-resolution multi-beam surveys rely on Real-Time Kinematic Differential Global Positioning System (RTK DGPS) data for tracking precise vessel position and elevation during the survey.[12] While extremely accurate, this system relies heavily on having a good "line-of-sight" with the satellite constellation to maintain a position fix. The nature of imaging a bridge requires the boat to frequently pass beneath the bridge and into areas where maintaining good satellite reception is difficult. In fact, it is not uncommon for sonar data to be mis-referenced or lost when positioned under a bridge. The amount of error introduced into the data can vary depending on many factors, including the height of the bridge (i.e. the existing freeboard between the waterline and superstructure), the number/location of satellites, and the location of the survey line relative to the satellites. To mitigate this error, RTK DGPS can be supplemented with other methods of obtaining a position, such as a Total Station.[13]

Some commercial off-the-shelf single-beam fathometers are also capable of using the Federal Aviation Administration (FAA) and U.S. Department of Transportation (USDOT) Wide Area Augmentation System (WAAS). The WAAS system utilizes ground reference stations positioned throughout the United States to correct for signal errors caused by ionospheric disturbances, timing, and satellite orbit errors. A surveyor with a WAAS capable GPS receiver can expect position accuracy up to five times greater than when using conventional GPS alone but not as good of accuracy as RTK DGPS. The same issues of line-of-sight around bridges and trees can cause position error similar to that encountered by RTK DGPS.[13]

6.0 PAST RESEARCH STUDIES

6.1 U.S. ARMY CORPS OF ENGINEERS 2006-2007 [19][20]

A series of case studies were conducted by the USACE in 2006-2007 to evaluate the use of sonar technologies for detecting scour of hydraulic control structures, specifically navigation dams. The technologies used were a lens-based multi-beam sonar unit and a multi-beam swath sonar system.

The first study of the Starved Rock Lock and Dam near Ottawa, Illinois was to evaluate the degree of scour underneath the apron leading to the stilling basin below the Starved Rock Dam. The lens-based sonar indicated with sufficient certainty that there was no evidence of the apron being undermined. The lens-based multi-beam was also able to identify several small defects in the concrete such as areas of section loss however, the depth of penetration could not be determined.

The second scour study in the spring of 2007 of the Mel Price Lock and Dam on the Mississippi River used a multi-beam sonar system to image both the upstream and downstream portions of the structure. The system was able to image a large area of unanticipated scour that was 12 feet wide and up to 10 feet deep relative to the adjacent channel bottom located immediately upstream of one of the gate bays.

6.2 MASSACHUSETTS DOT – 2008 [21]

A field study that compared the usefulness of 2-D sector-scanning sonar and side-scan sonar for underwater bridge inspections. The study concluded that vertical surfaces were easier to image with sector-scanning sonar than with side-scan sonar. Additionally, the sector-scanning sonar was able to get image data near the water surface where the side-scan sonar could not.

6.3 UNIVERSITY OF DELAWARE 2008 [22]

A study was conducted by the University of Delaware Center for Applied Coastal Research in which a sonar-based system was installed to monitor scour at the Highway 1 Bridge over Indian River Inlet in near real-time. The system consisted of two profiling sonar units mounted on the bridge piers and two Acoustic Doppler Current Profilers that were set up to automatically survey the inlet on the ocean side of the bridge twice daily. Using this method the team was able to accurately map the extent of the scour over time and the probable controlling cause of the scour hole.

The study concluded that although the initial capital outlay for this custom system was costly, the repeatability over time made it a cost effective alternative compared to successive traditional multi-beam or single-beam sonar surveys.

6.4 WISCONSIN DOT 2008 AND 2010 – SONAR FINDINGS VS. DIVER OBSERVATIONS [23]

Heavy deterioration of concrete substructures at a bridge in Wisconsin would have been difficult and time consuming for a dive inspector to accurately report and quantify. Sector-scanning sonar was utilized to map the extents of heavy concrete scaling below water. The sector-scanning sonar clearly indicated areas with exposed reinforcing steel. Additionally, relative depth of scaling could be examined based on darkness of shading, but actual penetration depth could not be obtain from the sonar data. For this reason, the case study utilized a diver to document depth of penetrations at each portion of the pier faces.

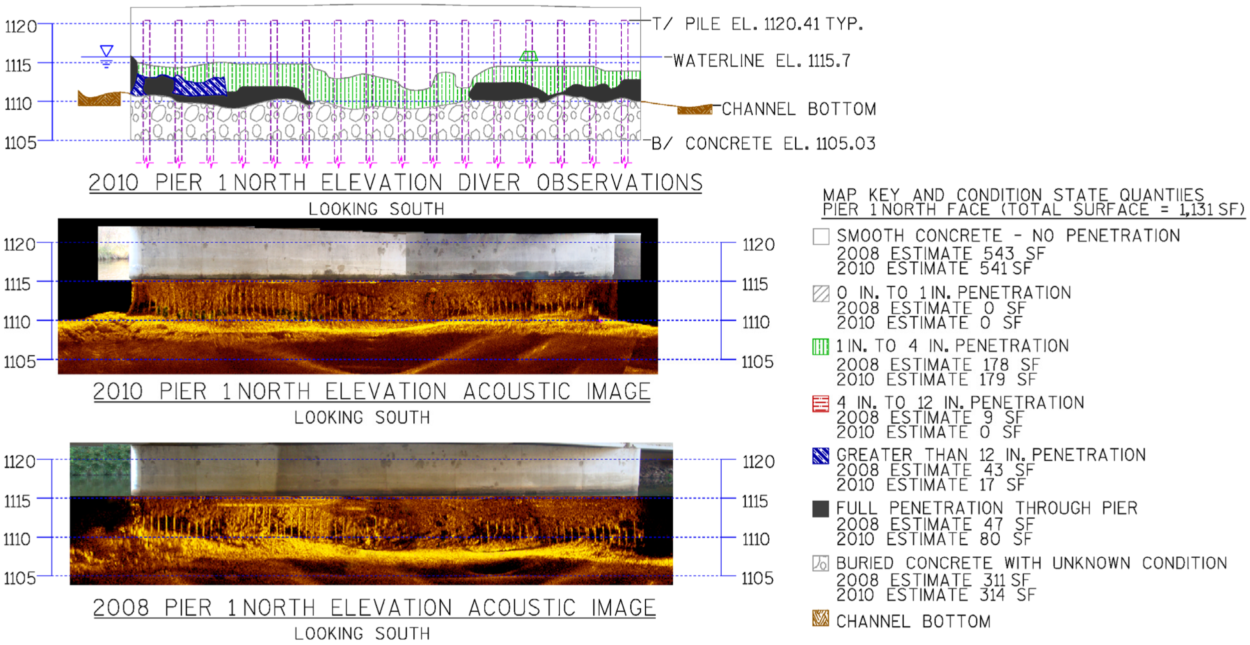

Figure 26. Sector-scanning sonar image of pier face (below) and diver interpretation of results (above).

6.5 QUEENS UNIVERSITY IN EUROPE 2009 – 2010 [24]

The Queens University study focused on the use of ground penetrating radar (GPR), in conjunction with a hydrographic sonar survey, for the purpose of identifying scour and scour infill around the submerged substructures of a bridge. Additionally, the study included a comprehensive listing of commercially available acoustic imaging devices.

The report concluded that GPR has several useful applications for underwater bridge inspection. It showed that the data gathered allows for the interpretation of depths of the river bed to form a contour map; the presence of rock vs. sediment in the channel-bottom material composition; and the likely distribution of sediment depths in the waterway.

It showed that GPR was useful for creating a baseline survey of a bridge where areas of scour infill could be detected and then further monitored during subsequent inspections. Bridge owners could then determine if the extent and severity was increasing and whether remedial actions needed to be taken.

It is important to note that the report did not cover whether GPR was able to assist in any other aspects of underwater bridge inspection such as determining physical defects in the substructures themselves such as cracks, corrosion, or the presence of voids.

6.6 IDAHO DOT – 2011 [25]

A field study with the primary purpose of determining the usefulness of sector-scanning sonar to aid in underwater inspection of highway bridges in the state of Idaho. The study included a small literature review and had three case studies which compared the quality of data gathered by sector-scanning sonar to the data gathered by a qualified inspection diver.

The conclusions of the report stated that cracks, horizontal penetration of voids, foundation undermining, extents of steel corrosion, presence of concrete scaling, and channel-bottom material composition could not be ascertained with the 2-D sector-scanning sonar that was being utilized. However, the diver was able to give detailed descriptions of each of the above items. Additionally, the type of construction material present below the water surface was also difficult to verify with the sector-scanning sonar technology compared to a diver's tactile observations.

The primary benefits of the sector-scanning sonar included producing detailed images of the channel-bottom profile including scour depressions, and imaging vertical components of submerged substructures, in waters too swift and turbulent for a diver. Another benefit was that the sector-scanning sonar was very portable and could be deployed from a small boat or the bridge deck.

One of the three case studies included acoustic imaging of bridge piers with turbulent currents measured at 5 feet per second. Although a dive inspection was not able to be performed at this bridge, the acoustic images were able to determine that three of the piers had no footing exposure and that one of the piers had footing exposure with 1 foot vertical undermining. However, the penetration dimension of the undermining could not be determined.

7.0 SONAR APPLICATIONS AND CASE STUDIES

7.1 GENERAL

The requirements for underwater bridge inspection procedures are well documented. Yet some bridge inspectors and owners have increasingly been turning to acoustic imaging technology to enhance inspection and documentation procedures. This trend has been accelerated based on the special needs of some bridge owners with a large number of bridges containing adverse site conditions such as zero visibility, high velocity currents, heavy debris, and extreme depth. Because these factors can limit a diver's ability to thoroughly inspect a bridge below water, enhancements such as acoustic imaging have been used as a supplement to ensure a thorough inspection. Potential applicability of acoustic imaging for bridge inspections are outlined in the below sections:

- 7.2 Rapid condition assessment.
- 7.3 Scour detection and documentation.
- 7.4 Underwater construction inspection.
- 7.5 Security threat assessment.
- 7.6 Documented visual representation of the entire underwater structure.
- 7.7 Enhancing diver safety and efficiency at challenging dive sites.

To date, acoustic imaging has been utilized at bridge sites in over thirty states including: California, Colorado, Delaware, Florida, Georgia, Idaho, Illinois, Indiana, Iowa, Kansas, Kentucky, Louisiana, Maine, Maryland, Massachusetts, Michigan, Minnesota, Missouri, Nebraska, New York, New Jersey, North Dakota, Ohio, Rhode Island, South Carolina, South Dakota, Tennessee, Texas, Virginia, Washington, Washington D.C., and Wisconsin.

7.2 RAPID CONDITION ASSESSMENT

Both natural disaster and man-made events can cause the need for emergency structural assessment. Natural disaster events include hurricanes, tornadoes, floods, earthquakes, and tsunamis. Man-made events can include vessel or vehicle impacts and dam breaks. Rapid condition assessment is often required immediately following an emergency event.

These emergency events can threaten the structural stability of a bridge, and decisions often cannot wait for adverse conditions to become more favorable for a dive inspection. The immediate need for a bridge closure decision can result in overly conservative closures requiring unnecessary lengthy detours. With acoustic imaging technology bridge owners can get important information about a structure during or soon after an event, whereas a dive inspection might have to wait weeks or months for the water to go down or for conditions to otherwise become favorable.

7.2.1 Iowa DOT, US-20 Vessel Impact Damage Inspection - 2008 [26]

The US-20 Bridge over the Mississippi River had three barge sections impact three different substructure units during flood conditions. One barge unit capsized and sank at the upstream nose of a pier. Local construction crews estimated that removal of the capsized barge section could take months. Sector-scanning sonar was used to quickly search for large scale impact damage and section loss of the concrete pier and to assess the channel-bottom configuration to ensure that water being deflected by the barge was not adversely contributing to scour of the foundation.

Figure 27. Sector-scanning sonar image of submerged barge at upstream nose of pier.

7.2.2 Texas DOT Hurricane Damage inspection - 2008 [27]

In the fall of 2008 Hurricane Ike struck Galveston Texas, an island in the Gulf of Mexico just off the Texas coast. As a result of the hurricane, the Rollover Pass Bridge was severely damaged. Water conditions consisted of low visibility and swift tidal currents that meant divers could only work for 15 minutes at a time during slack tide.

Due to the need to rapidly asses the condition of the bridge, the Texas DOT permitted the Center for Robot-Assisted Search and Rescue from Texas A&M University to deploy unmanned marine vehicles equipped with two types of sonar technologies (in addition to traditional video cameras and other sensors) to assess the bridge for scour and hazards to navigation.

One of the primary sensors was a lens-based multi-beam sonar unit to be used as an acoustic camera for scour evaluation and a side-scan sonar unit for mapping the debris field. Because of these technologies the bridge owner was able to find that there was no sign of scour at the bridge or debris that could present a hazard to navigation. This study has obvious implications for other aspects of bridge assessment mentioned above such as diver safety and scour evaluation.

7.2.3 Illinois DOT Vessel Impact Damage Inspection - 2009 [28]

Sector-scanning sonar was used in the rapid assessment of a bridge incident in 2009 where an emergency inspection of a bridge was required due to a barge striking and overturning a steel sheet pile protection cell adjacent to a State Route bridge over the Illinois River in Central Illinois. A sector-scanning sonar unit was used in this case to create a highly detailed “big picture” of the barge impact, depicting to-scale the protection cell position and damage, as well as how it related to the bridge substructure.

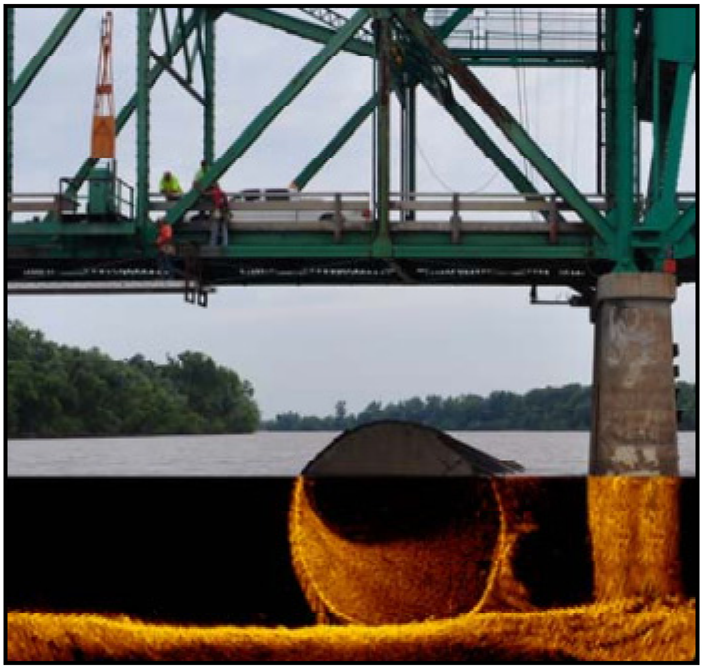

Figure 28. Sector-scanning sonar image of damaged steel protection cell.

7.3 SCOUR DETECTION AND DOCUMENTATION

The number one cause of bridge failure in the United States is scour. This makes it paramount for bridge owners to be able to efficiently and safely be able to assess the presence of scour at a bridge site. According to the 2011 NBI data over 7,500 highway bridges are rated “scour critical”. The presence of scour can often be difficult for an inspection diver to detect for a variety of reasons and this makes underwater imaging technologies extremely useful.[29]

In addition to performing hydrographic surveys, fixed scour monitoring systems can be established for continuous scour monitoring at a specific site. A fixed scour monitoring system means that it is permanently or semi-permanently attached to a structure to repeatedly monitor a specific area. According to the Transportation Research Board, in 2009 over 30 states had fixed scour monitoring installations and over 60 of those installations utilized at least one sonar system.[29]

7.3.1 Iowa DOT Bridge Embankment – 2011 [30]

During the summer months of 2011, the Missouri River water levels were sustained near record levels for several months. The sustained high water levels caused the main river channel to re-route itself and a new channel was established adjacent to the embankment leading up to the STH 175 Bridge abutment. Traditional hydrographic survey techniques were unable to produce depth data in shallow water near the large stones due to difficulties of maneuvering a boat in the swift currents. While construction crews worked to place protective riprap along the embankment, sector-scanning sonar was used to document whether the slope was staying in position or continuing to wash away by the tremendous forces of the flood waters.

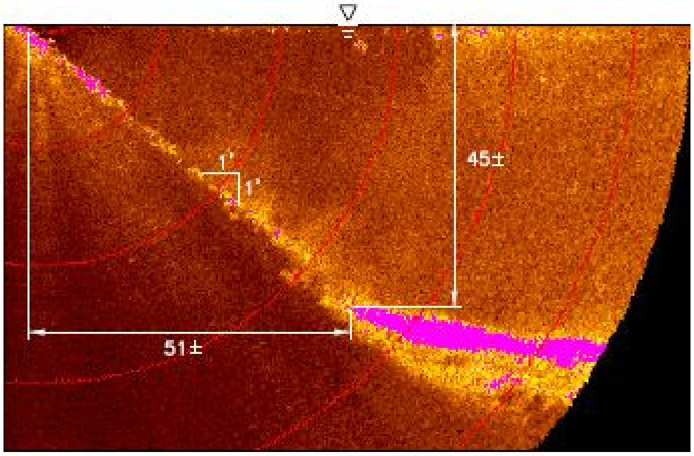

Figure 29. Verification of highway embankment slope erosion.

7.3.2 Nelson County Kentucky Scour Documentation – 2011[45]

During the spring of 2011 bridge inspectors attempted to take depth sounding at the KY 84 Bridge over the Rolling Fork River Slough in central Kentucky. Due to the extreme flood conditions and swift currents, it was nearly impossible to get accurate depth data at the piers. An inspection crew used sector scanning sonar to create an image of the pier in question and measured the length of the exposed piles.

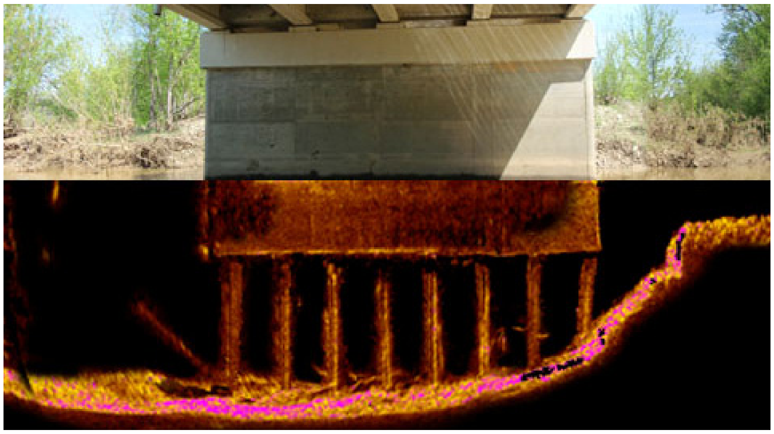

Figure 30. Acoustic image of undermined bridge pier.

The lengths of the piles were compared with the as-built plans and the remaining embedment lengths of the piles were determined. The imaging assisted the engineers in determining that only 2 feet of pile embedment was remaining at the downstream end of the pier and the bridge was closed until repairs could be made. When flood waters receded, the river was dewatered to perform repairs. Figure 31 shows a dewatered picture of the bridge pier that is imaged in Figure 30.

Figure 31. Photograph of bridge pier in Figure 30 taken after dewatering.

7.3.3 Shallow Water Scour Investigation – Japan [44]

This case study involved the use of a mechanical scanning multi-beam sonar system to measure the scour of a bulkhead along the banks of the Susobanagawa River in Japan. The site conditions required the use of a system that could operate in approximately 3 feet of water and be able to scan a vertical surface for undermining. The team was able to produce 3D-point cloud data of the area that showed that more than half of the bulkhead was undermined with a maximum of almost 5.5 feet of penetration beneath the structure. In this instance the mechanical scanning multi-beam sonar unit was able to produce side-elevation data that traditional downward-looking swath multi-beam sonar systems could not provide.

7.4 UNDERWATER CONSTRUCTION INSPECTION

Underwater imaging technologies can be used in all phases of construction; from pre-construction planning, through the construction phase, to verifying as-built information.

Lens-based multi-beam sonar systems have seen successful used in the offshore construction industry and have possible applications for bridge construction. Hull mounted and diver-held units have been used to locate and place underwater pipes as well as inspect North Sea drill platforms. Possible applications in bridge construction include inspection of formwork and placement of riprap.[31]

Another construction related business that heavily utilizes sonar technology is the dredging industry. Everything from single-beam fathometer surveys to side-scan sonar and multi-beam swath surveys have been used to quantify and classify river channels and the sea-bed. The primary uses for sonar in dredging is the charting of access channels for safe navigation of dredging vessels, the detection of obstacles that could damage the dredging head, and to map the composition and distribution of the seabed sediments, and calculate volumes.[32] Many dredging operations are made more efficient by combining two or more sonar systems for simultaneous operation. For instance, a side-scan sonar system can be used because of its superior range to detect potential obstacles while a shorter range multi-beam system creates detailed geo-located point cloud data at the same time. Careful consideration needs to be given to the deployment and location of the different systems to guarantee the best results.[32]

7.4.1 Wisconsin DOT Bridge Scour Construction Inspection – 2009 [33]

A routine underwater inspection revealed undermining of a pier foundation (shown by the white line below). A contractor was hired to place riprap at the pier to prevent future undermining. The Wisconsin DOT utilized sector-scanning sonar to obtain visual confirmation that the riprap being placed by the contractor was performed as intended.

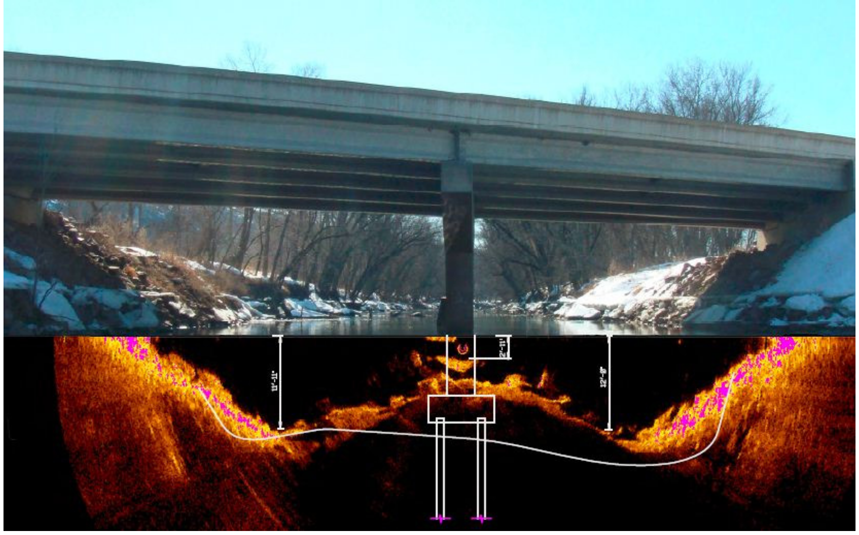

Figure 32. Verification of riprap placement at Undermined Pier.

7.4.2 Indian River Inlet, DE Dockwall Riprap Placement – 2009 [28]

One example case study at the Indian River Inlet in Delaware used sector-scanning sonar to verify contractor work in the remediation of scour. On a section of sheet pile bulkhead along the Indian River where there was difficulty assessing the extent of scour with divers due to adverse conditions, a scanning sonar unit was deployed to check the specified placement limits of rock material. Using this method, deficiencies in the contractor's work were found and the resulting images were used to direct the placement of additional riprap.

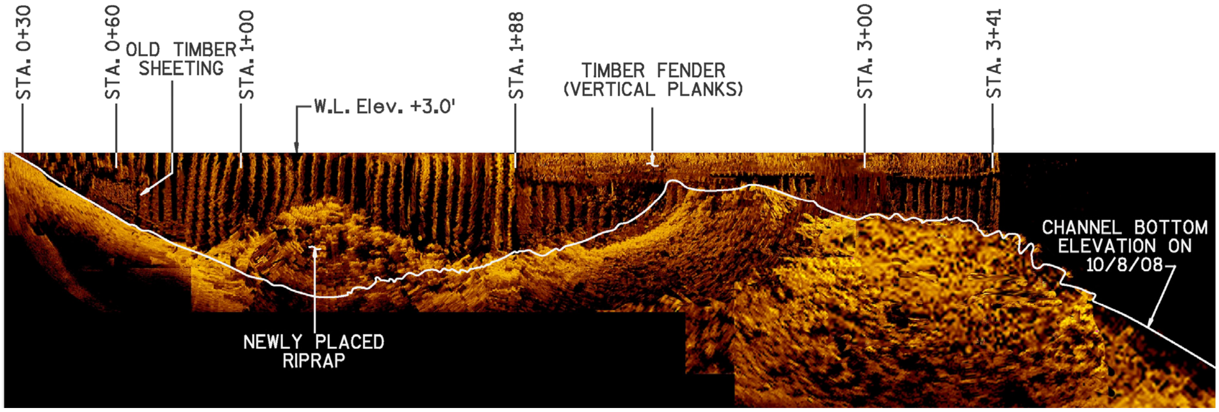

Figure 33. Verification of riprap placement along sheet pile bulkhead.

7.5 SECURITY THREAT ASSESSMENT

The ability to image underwater structures has obvious security implications for ports, harbors, and bridges in the United States. The potential applications are numerous and include scanning for explosives and detecting intruders. All types of commercially available imaging sonar has been used for this purpose and there are several cases showing that acoustic imaging technologies have proven to be an efficient and reliable way to accomplish this.

7.5.1 Ship hull Scanning - 2007 [34]

In 2007 a process was developed utilizing a combination of a narrow-aperture upward-looking sonar system with multiple beam-formed imaging sonar scans to successfully image the underwater portions of ship hulls for possible explosive devices. This proof of concept shows that it is possible to use sonar imaging technology to locate anomalies on underwater structures. This could be further developed for use in security applications of other structures such as the below-water portions of high-profile or at-risk bridges.

7.5.2 Major Events Security – 2004, 2005 [35] [36] [37] [38]

In late 2004 and early 2005, the University of South Florida Center for Ocean Technology working with various government agencies and manufacturers helped provide security for two large events: the 2004 Republican National Convention and Super Bowl™ XXXIX. These case studies showed that acoustic imaging technologies can rapidly assess large structures in security applications. The U.S. Coast Guard used their real-time multi-beam sonar system to quickly and thoroughly scan over 20 miles of dockwalls, ship hulls, bridge piers, and bridge abutments for potential "targets" that could indicate terrorist activity. The underwater acoustic imaging technologies used there were a real-time multi-beam sonar system and a lens-based 2-D multi-beam sonar system.

Security officials conducted initial baseline scans in both New York and Florida in a fraction of the time that it would have taken for a traditional diving inspection. All of the data was accurately geo-referenced using an internal navigation system. Over 1,000 "objects of interest" were identified in Florida alone and then narrowed down to seven when the images were sent to the control center. At this point police divers were used to investigate each object. After a hands-on inspection by divers they were found to be of no threat. Subsequent scans could then be conducted and compared to the baseline to identify new potential threats.

7.5.3 Intruder Detection Sonar Systems [39] [40]

Sonar technologies have also seen extensive use for underwater intruder detection. There are many companies that manufacture such systems and they have been installed to monitor sensitive areas such as: offshore oil platforms, coastal energy terminals, nuclear power facilities, naval bases, and VIP compounds. These systems could easily be adapted to monitor high-value bridges for divers or swimmers attempting to attach an explosive device or otherwise damage the structure.

7.6 VISUAL REPRESENTATION OF THE ENTIRE UNDERWATER STRUCTURE

One of the main advantages of underwater imaging technology is the ability to image a structure regardless of water clarity. Where other optical technologies or a diver might allow an inspector to visualize parts of a structure, several types of sonar allow an owner to see images of a structure in its entirety. It is easy to see that several of the examples listed above could be used to visualize a whole structure. Additionally, several other studies have been completed to examine the feasibility of this.

7.6.1 Gulf of Mexico - 2005 [41]

During the 2005 hurricane season, hurricanes Katrina and Rita destroyed many drilling platforms in the Gulf of Mexico. The platforms that were destroyed were called "downed" platforms and in order to safely and efficiently decommission them in little to no water visibility, several different types of sonar technology were used in unison. For initial site reconnaissance, side-scan sonar was used because of its ability to scan large areas in a relatively short amount of time. Once the location of large features were found, a sector-scanning sonar system mounted on a tripod was used to further clarify the data and produce high resolution 2-D images of the downed platforms. These first two steps were important for locating potential hazards for ships and diving operations. The final phase of the operation involved using a multi-beam echosounder to produce detailed point cloud data of the downed platforms. The multi-beam units were used in the traditional downward looking swath configuration, as well as mounted to an ROV in an innovative side-looking configuration. This was done in order to minimize shadows and help visualize the entire volume of the debris field. By taking advantage of the relative strengths of several sonar technologies and deployment techniques, the team was able to produce the data needed to safely decommission the wells.

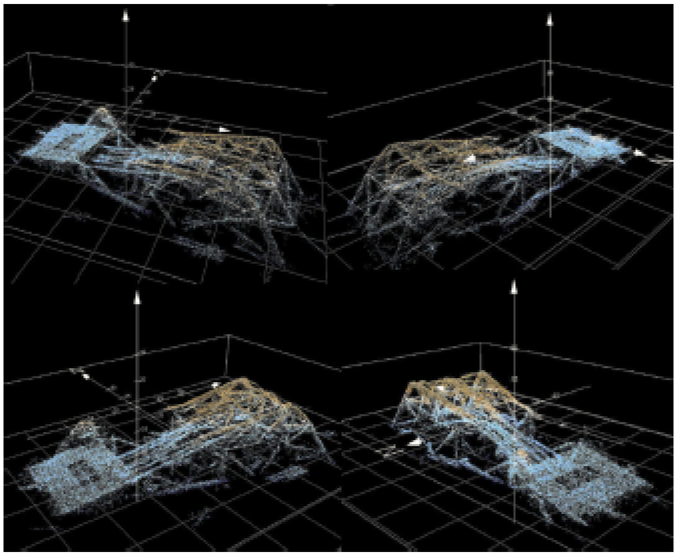

Figure 34. Point cloud models of "downed" platforms. (Permission to be obtained)

7.6.2 Freeport Bahamas Dockwall Assessment – 2010[43]

Underwater inspection of a limestone dockwall revealed that large surface irregularities existed. Accurate documentation of void proved to be time consuming and cumbersome for dive inspectors. In order to provide an accurate depiction of underwater conditions, multi-beam sonar was utilized to map the face of the wall. The resulting data provided for accurate volume calculations that were used estimate repair quantities.

7.7 ENHANCING DIVER SAFETY AND EFFICIENCY

As described in the cases above, underwater imaging technology has a large impact on diver safety and efficiency. As previously stated; technologies such as lens-based multi-beam sonar and sector-scanning sonar have the ability to generate data that can then be used to direct a diver to or away from a specific area.

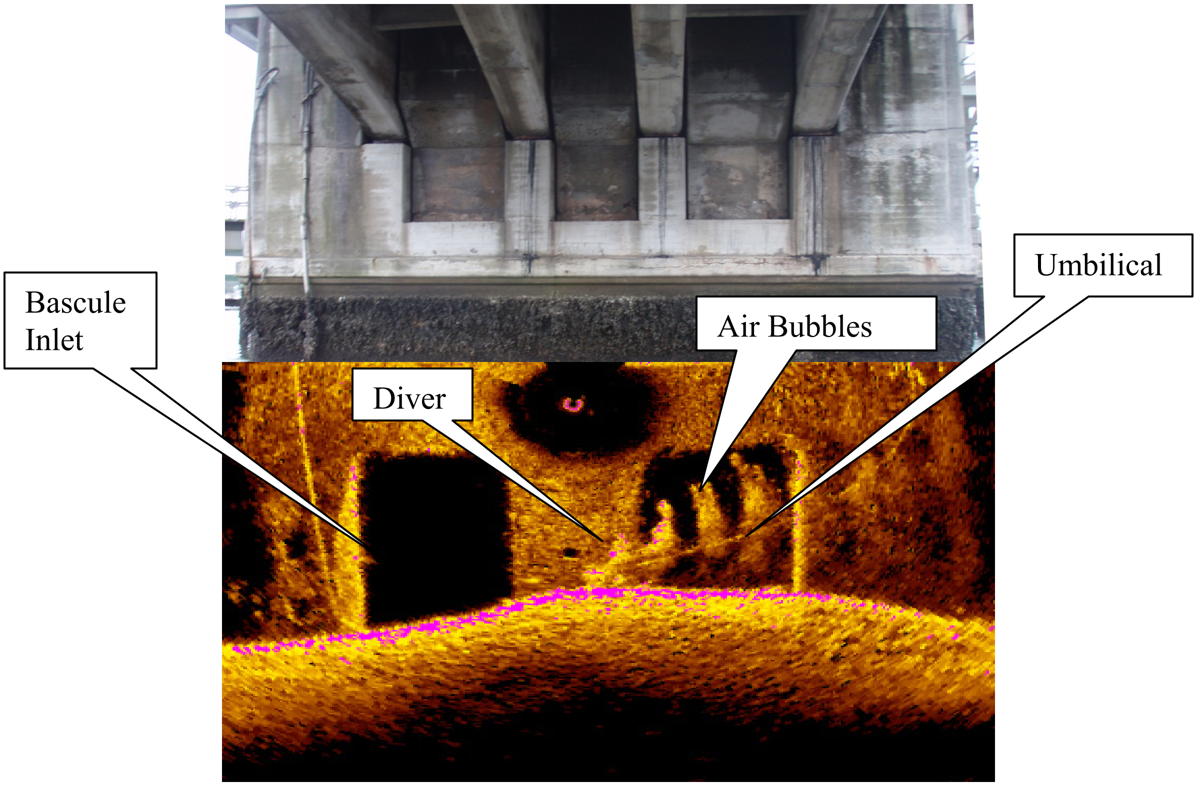

Figure 35. Sector scanning image of diver.

7.7.1 LNG Terminal Construction Qatar 2005[42]

The LNG Terminal Construction Project utilized real-time multi-beam sonar technology to increase production efficiency and improve the health and safety of dive inspectors during the construction of a breakwall in the country of Qatar. The project required the precise placement of thousands of precast concrete tetrapods along the seabed. The traditional placement method involves the use of divers to visually help rotate and place the tetrapods using cranes. This method is time consuming and dangerous. To help reduce the dangerous exposure to divers, a real-time multi-beam sonar system and underwater video camera were installed on the excavator's boom to allow the operator to view the orientation of the tetrapods in any water conditions. Fully geo-referenced 3-D survey data was superimposed onto the real-time sonar image to further aid the operators in the geographic position, placement, and orientation of the tetrapods. Dive inspectors were still used for the final verification of the work however, use of the real-time multi-beam sonar system resulted in an increased average daily production of over 300 percent.

Figure 36. Real-time multi-beam sonar image of concrete tetrapod unit at left, and above water photograph at right. (Permission to be obtained)

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