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Sensors and Processing for Pipe, Riser, Structure, and Equipment Inspection to Provide Detailed Measurements, Corrosion Detection, Leak Detection, and/or Detection of Heat Plumes from Degraded Pipeline Insulation

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ABSTRACT

Converting Ultra Deepwater (UDW) resources into economic reserves can be a very time consuming and expensive process. In addition, pipeline failures, flow restrictions and production downtime can further increase costs of exploiting these reserves. These costs can all be reduced with faster, more efficient, and more effective techniques for underwater survey and inspection.

Existing methodologies involve visual inspections, and/or the use of lower frequency sonar equipment that does not have the resolution and sensitivity of the proposed technology. Visual inspections require divers or video cameras, both of which are limited by poor visibility. Underwater laser systems can supply comparable resolutions to the proposed systems, but are also vulnerable to poor water quality conditions. Existing acoustic measurement (metrology) solutions either take many steps to complete or lack the resolution and sensitivity necessary (conventional multibeam sonar) to enable detailed measurements and detect subtle features such as corrosion, leaks, or heat plumes.

The goal of this effort was to develop critical sensing capabilities that improve efficiency, reduce time and costs, reduce rework, and improve safety and environmental performance when developing, exploiting, and producing UDW resources. The tested capabilities were aimed at reducing costs, increasing efficiency, and enhancing environmental performance. UDW resource exploitation will be increased with accelerated development and improved pipeline delivery of petroleum products.

The project involved research and testing efforts in both controlled indoor tanks environments and offshore environments. Multiple projects and applications were advanced and matured. One technology, 3D scanning sonar metrology, is now in active use globally in multiple oil and gas applications as direct outcome of this RPSEA-funded project. Many technology transfer activities were conducted including two presentations at the Offshore Technology Conference OTC and a publication in Sea Technology magazine.

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EXECUTIVE SUMMARY

Converting Ultra Deep Water (UDW) resources into economic reserves can be a very time consuming and expensive process. In addition, pipeline failures, flow restrictions and production downtime can further increase costs of exploiting these reserves. These costs can all be reduced with faster, more efficient, and more effective techniques for underwater survey and inspection.

Existing methodologies involve visual inspections, and/or the use of lower frequency sonar equipment that does not have the resolution and sensitivity of the proposed technology. Visual inspections require divers or video cameras, both of which are limited by poor visibility. Underwater laser systems can supply comparable resolutions to the proposed systems, but are also vulnerable to poor water quality conditions. Existing acoustic measurement (metrology) solutions either take many steps to complete or lack the resolution and sensitivity necessary (conventional multibeam sonar) to enable detailed measurements and detect subtle features such as corrosion, leaks, or heat plumes.

The goal of this effort was to develop critical sensing capabilities that improve efficiency, reduce time and costs, reduce rework, and improve safety and environmental performance when developing, exploiting, and producing UDW resources. The tested capabilities were aimed at reducing costs, increasing efficiency, and enhancing environmental performance. UDW resource exploitation will be increased with accelerated development and improved pipeline delivery of petroleum products.

The project involved applying BlueView's acoustic Blazed Array technology towards developing critical sensing capabilities that improve efficiency, reduce time and costs, reduce rework, and improve safety and environmental performance when developing, exploiting, and producing UDW resources. These goals will be accomplished by leveraging the enhanced fidelity of a Department of Defense (DoD) fueled and commercially-matured Blazed Array technology and products in concert with world-class partners to rapidly develop and field water-clarity-independent sensing solutions to enable:
Detailed physical measurements of underwater pipes and structures for inspection, metrology, and assessment of deformation, deflection, curvature, and anode condition,
Detection and identification of external corrosion, pitting, and biologic fouling,
Detection and quantification of gas or petroleum product leaks, and/or
Detection and quantification of heat plumes resulting from cracked or degraded pipeline insulation.

The Blazed Array technology was developed as part of a series of government contracts awarded to the University of Washington (UW) and BlueView Technologies from US government organizations including US Office of Naval Research (ONR), US Navy Explosive Ordnance Disposal Technology Division, PMS-EOD, PMS-LMW, DARPA, and NOAA organizations. The Blazed Array technology was developed by Dr. Lee Thompson while conducting research at UW and draws on concepts from optics, digital signal processing, and acoustics. When this technology was transitioned to BlueView from the University of Washington in late 2004, it was combined with commercial investment, a strong startup team, and local medical acoustics manufacturing, electronics, and image processing expertise to develop a robust, versatile, and reliable

core architecture. This core architecture has formed a solid foundation for hundreds of commercial products delivered to oil and gas, commercial, and military markets and scores of custom engineered-to-order Autonomous Underwater Vehicle (AUV) sensor systems delivered to US and NATO navies.

The project involved research and testing efforts in both controlled indoor tanks environments and offshore environments. Multiple projects and applications were advanced and matured. One technology, 3D scanning sonar metrology, is now in active use globally in multiple oil and gas applications as direct outcome of this RPSEA-funded project. Many technology transfer activities were conducted including two presentations at OTC and a publication in Sea Technology magazine.

During this project the Technology Readiness Level (TRL) of multiple technologies were advanced as shown below.

Spool Piece Metrology
Multiple onshore tests completed with industrial partners and then moved offshore with very successful results.
Multiple spools successfully installed in offshore operations globally to date.
TRL2 TRL5 TRL5 TRL8
(BV IR&D) (RPSEA funding)

Gas in water detection
Open water testing completed in Q1 of 2011
TRL4 TRL6 (RPSEA funding)

Liquid in water detection
Testing completed in Q1 of 2011
TRL2 TRL3 TRL3 TRL4
(BV IR&D) (RPSEA funding)

<u>Heat Leak Inspection -</u> (see report in Appendix B)
Initial tank testing completed in early Q4, 2011
Larger scale indoor testing completed with Chevron in Q2, 2012
TRL1 TRL3 TRL3 TRL5-6
(BV IR&D) (RPSEA funding)

Experimental Methods:

Spool piece metrology

To test the feasibility of applying 3D acoustic scanning for underwater spool piece metrology applications, BlueView's BV5000 system utilizes its high resolution multibeam sonar technology and a precision mechanical scanning unit to create a 3D scanning sonar that operates as an acoustic analogue to optical scanning laser systems. Therefore, an optical laser system provided ideal 'ground truth' data for comparison. However, the inherent laser attenuation limitations and air/water medium differences needed to be overcome. A flooding drydock facility was found to be an excellent venue to successfully address these challenges and collect comparison datasets with standard terrestrial laser scanner systems. Pipes were arranged when the dry dock was empty. A 3D laser scanning system was used to collect very accurate 3D survey data of the pipe's angles, ranges, and surrounding structures. The area was then flooded with salt water and a BlueView BV5000 3D scanning sonar was placed and operated in several locations to collect acoustic survey data to compare with the "ground truth" optical laser data. Because the BV5000 sonar provides very clean, high resolution data (much like a laser scanner) and in a standard laser scanner format (point clouds), conventional laser-scanner software could be easily used to manipulate, process, and compare both the laser and BV5000 data.

Several dry dock trials were conducted in 2010 and 2011 to compare the output of a BV5000 system to a conventional laser scanner. Figure 1 shows a picture of the dry dock during setup of one of the trials in Peterhead, Scotland. As seen in Figures 2 and 3, the BV5000 data matches very closely with the laser scanned measurements

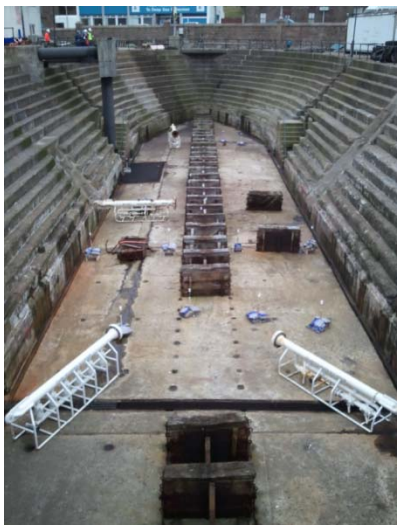

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Figure 1: Dry dock setup in Peterhead, Scotland

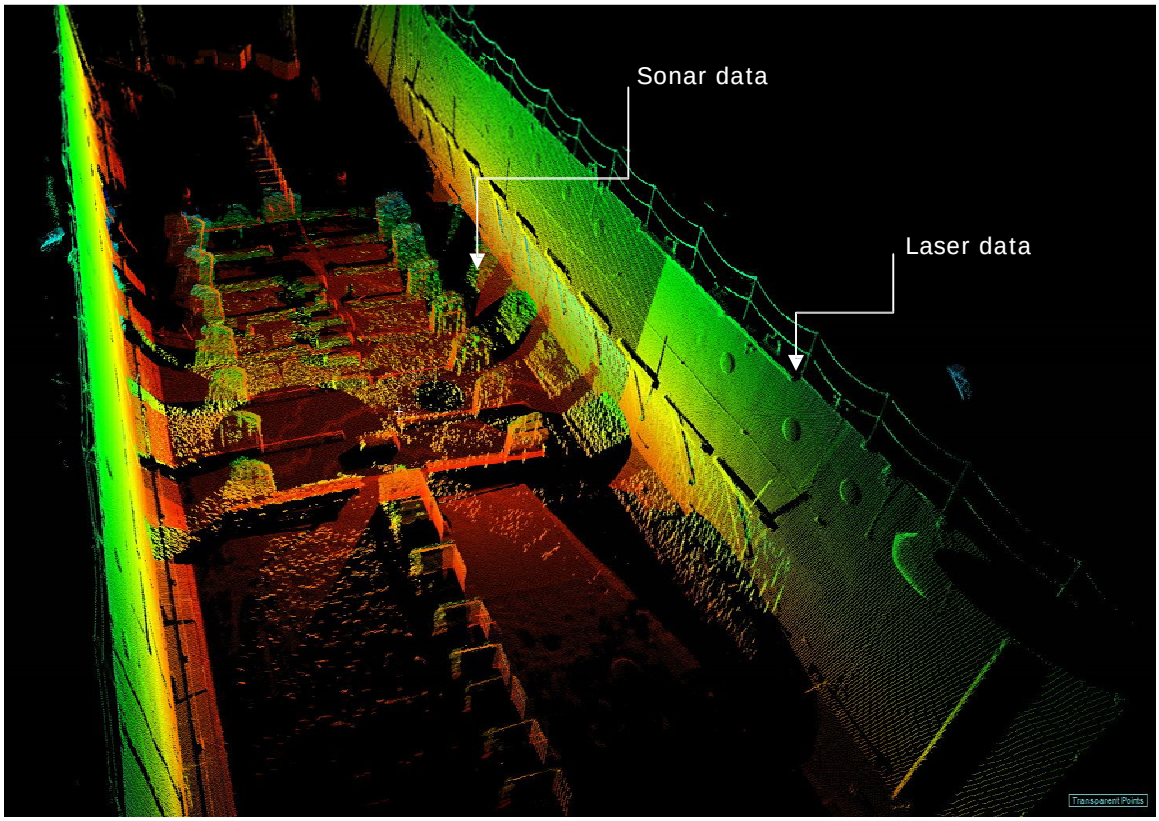

Figure 2: Example of preliminary metrology measurement uncertainty testing results collected on 11/30/09 in Aberdeen, Scotland.

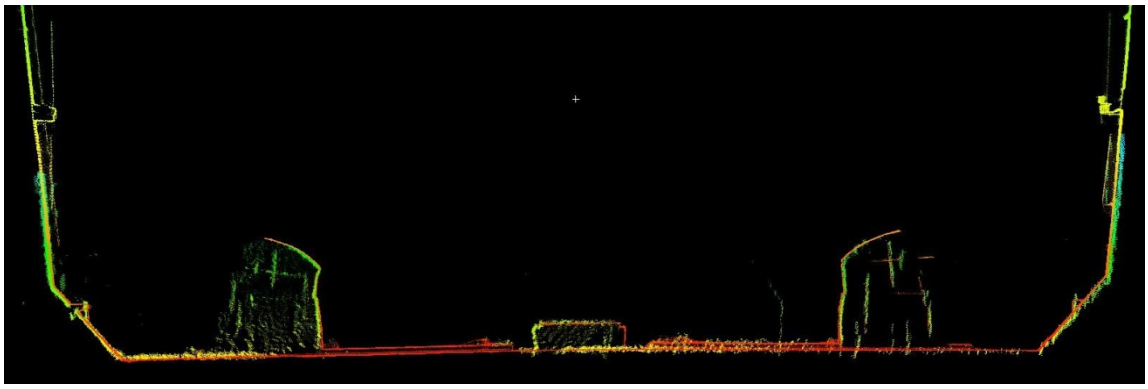

Figure 3: A slice taken through the point cloud at 6 meter range shows close agreement between BV5000 and laser scanned results.

Detection and quantification of gas or petroleum product leaks

In order to test BlueView's imaging sonar technology for the detection of suspended oil in water, test were conducted using carefully sealed bags of oil suspended at different ranges, and tested at different sonar frequencies. As a control test to ensure the bags themselves where not picking up the oil, similar test were done with water filled bags and shown not to produce the strong acoustic returns. Figure 4 shows an example of the oil filled bags used for testing. Figure 5 shows a screen capture of the acoustic return off the oil bag during the testing.

Figure 4: Photo of one of the oil filled bags used for testing oil detection with BlueView's acoustic imaging systems.

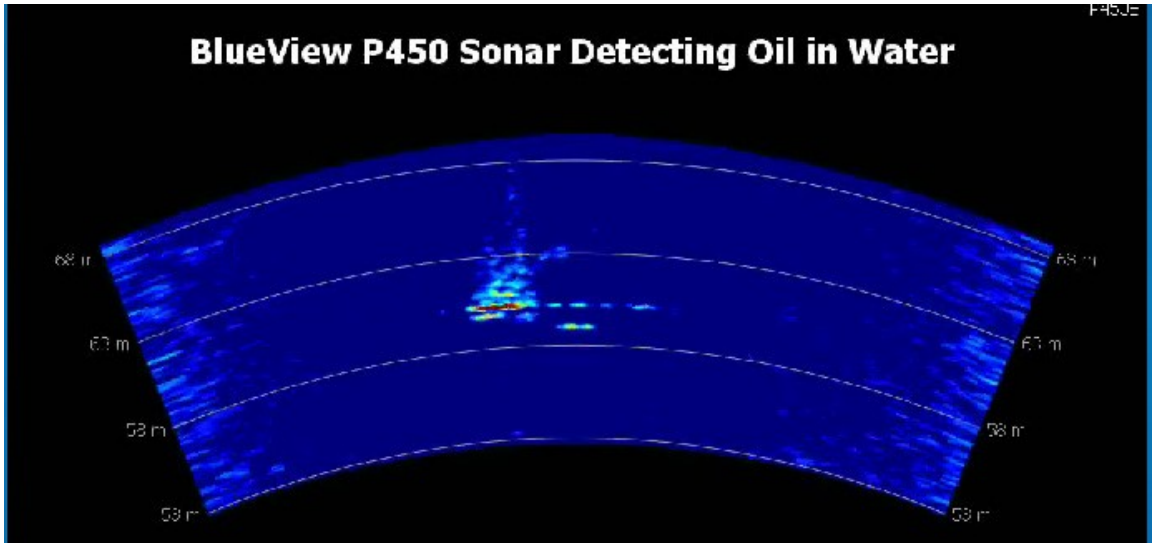

Figure 5: Screen capture showing the acoustic return at 63m range of a small oil filled bag suspended in the water column. A frequency of 450kHz was used during this test.

Detection and of heat plumes

The objective of the test discussed in this report was to examine the capability of BlueView's technology for detecting heat plumes via density differences in an environment that better resembled subsea infrastructure. The testing scenario involved inflicting progressive levels of damage to the insulation on a subsea pipeline sample filled with hot water. As flaws were introduced, two methods of sonar scans were performed: dynamic scans, in which the sonar would rotate about an axis at a fixed distance from the pipe, and static scans, in which the sonar would remain stationary and video feed was taken of the live scan window.

Testing was completed at the University of Washington School of Oceanography in their 13-foot deep salt water test tank. The pipeline sample used in the tests was approximately 6 feet long with a 6-inch outer diameter. This pipeline sample was coated with 2-3/4 inches of multilayered insulation. Heated water was cycled through insulated tubing into the pipeline using a small pump to simulate the hot fluid which would be present in real world operations. Additionally, the ends of the pipeline sample were capped and insulated to prevent heat loss while the pipe sample was in the test tank. Thermocouples were used to collect temperature data at various locations of the testing flow system. These locations included the inlet and outlet of the pipe sample, the heating tank temperature, the ambient tank temperature, the in-hole temperature of the induced damage, the plume temperature, and the ambient temperature at plume depth in the test tank.

In order to perform the test, the heating water was first heated to approximately 200° F while continuously being pumped through the pipeline sample. Sufficient time was allotted for the temperature distribution within the pipe to equilibrate and the pipeline was then lowered to the bottom of the tank in order to obtain a baseline scan. During this baseline scan, it was found that the thermocouples interfered with the scan output, so the thermocouples were removed after adequate temperature readings were obtained. Once the baseline sonar scan was attained, the first simulated damage was induced on the pipe. A ½-inch diameter hole was drilled to emulate insulation pitting, and more severe damage was introduced later in the test to simulate other types of insulation failure. As each flaw was introduced, temperature readings were taken and multiple sonar runs were completed to obtain the sonar's threshold for displaying heat plumes.

Table 1. This table shows the various flaws introduced to the insulated pipe sample.

Step	Flaw Method	Failure Scenario
0	Unaltered pipe – no added flaws	N/A
1	Drill Bit - 1/2 through insulation	Insulation pitting
2	Drill Bit - through insulation	
3	~3mm saw blade - 1/2 through insulation	Insulation crack
4	~3mm saw blade - through insulation	
5	~10 sq in section removed - 1/2 through insulation	Dropped object, anchor drag, gross insulation failure
6	~20 sq in section removed - through insulation	
7	~20 sq in section removed - 1/2 through insulation	
8	~20 sq in section removed - through insulation	

The testing rig followed the basic outline as seen in Figure 6, with some small modifications. The inlet and outlet of the system were on the same end of the pipe, as seen Figure 7. However, linear flow was still present in the system as the inlet pipe extended inside to the end of the insulated pipe sample, as seen in Figure 8.

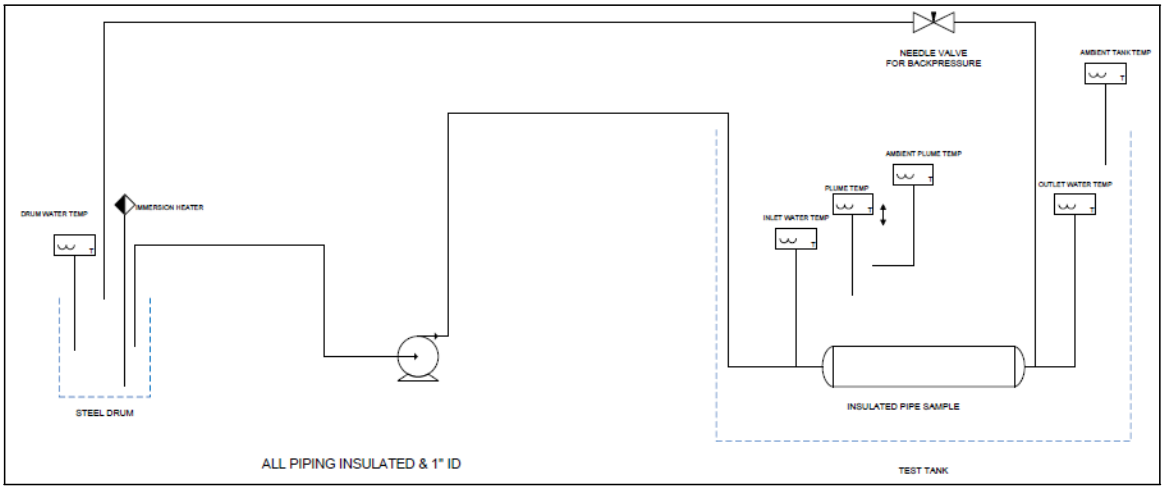

Figure 6. This schematic is a basic outline of the test rig set up.

Figure 7. This camera image shows the end of the insulated pipe which contains both the inlet and outlet of the hot water circulation system. The inlet extended to the end of the pipe to allow linear flow.

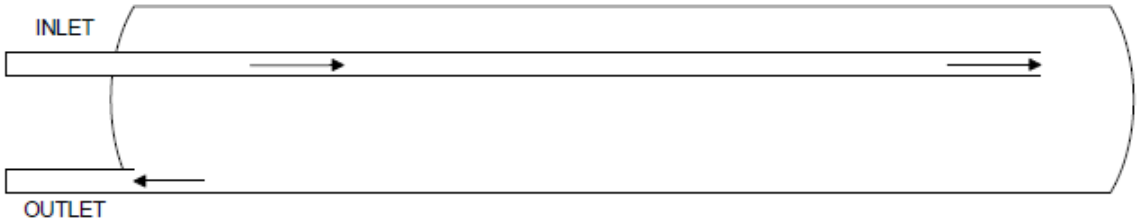

Figure 8. This simple schematic shows the extension of the inlet pipe inside the pipe sample.

During the test, the pipeline sample was placed on wooden blocks to prevent it from rolling while being scanned with the sonar. Additionally, rods were mounted to the ends of the pipeline for securing instrumentation during testing operations. Once the pipe was lowered underwater, as seen in Figure 9, the BlueView sensor was tested for each insulation flaw detailed in Table 1, with the flaws progressively increasing in severity. The sensor was tested statically at a distance of both 3 feet and 7 feet from the pipe sample. Dynamic scans were also taken at these distances, using 45° and 90° sweeps at 1°/s angular velocity. Testing was performed in this manner to determine the resolution of the sensor for detecting heat plumes, relative to temperature differences and the size of insulation flaws. The flaws were created using a ½-inch drill bit, a circular carbide tipped saw blade, and a hammer when necessary.

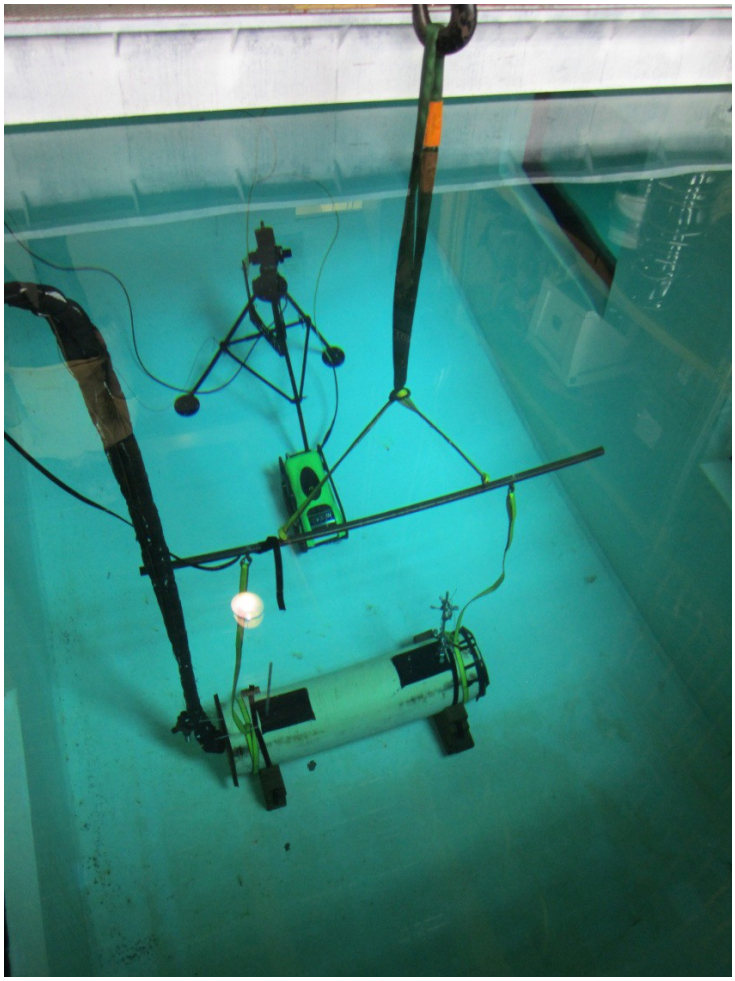

Figure 9. This image shows the underwater test set up, the sonar on a tripod with a small ROV to move the sonar and the pipe submerged and place on blocks to prevent rolling.

RESULTS AND DISCUSSION

Spool Piece Metrology

The spool piece metrology application received particular focus in the RPSEA effort because of the strong interest from multiple service provider partners and the high potential for increased efficiencies and hence cost savings. Consequently, the spool piece metrology application was rapidly matured into a new offshore operational capability.

In order to verify the accuracy of the BV5000 system, BlueView conducted a series of dry dock trials throughout late 2010 and early 2011 to compare the output of a BV5000 system to a conventional laser scanner. In each trial, the dry dock was outfitted with sample pipe assemblies and reference targets. Initially, the dock was drained and scanned with a terrestrial laser scanner. Next, the dock was flooded and the BV5000 was deployed and collected multiple scans. Finally, the BV5000 point cloud was superimposed on the laser data. In all cases, the BV5000 produced results which were extremely close to the laser scans. At ranges less than 20m, typical range accuracies were on the order of 3cm (translational) and 1 degree (angular). Over a 40m baseline, the BV5000 measurement agreed with the laser scanned data to within 10cm. For a more detailed schedule of measurements, please see Tables 2 - 4 below.

Peterhead, September 2010 Partners: Seatronics, Technip, StarNet		
Flange Separations		
BV5000-1350 (meters)	Laser (meters)	Difference (meters)
4.524	4.507	0.017
12.858	12.898	0.040
30.111	30.167	0.056
13.180	13.217	0.037
30.352	30.381	0.029
17.330	17.334	0.004
Flange Relative Heading*		
BV5000-1350 (deg)	Laser (deg)	Difference (deg)
61.63	62.56	0.94
65.12	65.33	0.21
149.44	148.69	-0.75
53.29	52.12	-1.17
148.65	148.75	0.10
84.58	83.37	1.22

Table 2: Initial metrology trials produced strong results, with typical range accuracies on the order of 3-5 cm (translational) and 1 degree (angular)

Fraserburgh, March 2011 Partners: StarNet		
Flange Separations		
BV5000-1350 (meters)	Laser (meters)	Difference (meters)
3.562	3.494	0.068
30.684	30.635	0.049
39.057	38.987	0.070
30.305	30.250	0.055
38.922	38.825	0.097
8.880	8.825	0.055
Drydock Corner-to-Corner		
Flange Relative Heading*		
BV5000-1350 (deg)	Laser (deg)	Difference (deg)
53.77	53.26	0.52
55.93	56.93	-1.00
153.52	154.12	-0.60
70.36	69.84	0.51
152.65	152.62	0.03
82.41	82.79	-0.37

Table 3: Follow on metrology trials confirmed the range accuracies observed in Peterhead
*Angular estimates based on multiple measurement

Stabbert, March 2011		
Spherical Reference Target Separation		
BV5000-1350 (meters)	Laser (meters)	Difference (meters)
6.699	6.698	-0.001
8.917	8.944	0.027
15.092	15.125	0.033
7.991	7.980	-0.011
22.997	23.057	0.060
8.393	8.425	0.032

Table 4: A final round of dry dock trials underlined the consistency of the BV5000 system

After multiple onshore trials and system refinements, in September of 2011 the first offshore spool piece metrology job was completed in the North Sea by Technip with two spool pieces successfully installed. It was reported that this job was completed in less time than would have been required using conventional long baseline acoustic positioning and diver techniques. As a result of this success, multiple additional jobs have been initiated. Three spool piece metrology jobs are currently underway in the North Sea at the time of writing and others are in initial planning stages.

Detection and quantification of gas or petroleum product leaks

Several sonars between the operating frequencies of 450kHz and 1.35MHz were tested. The maximum return in dB was calculated at a variety of ranges. The results are plotted in Figure 10 below.

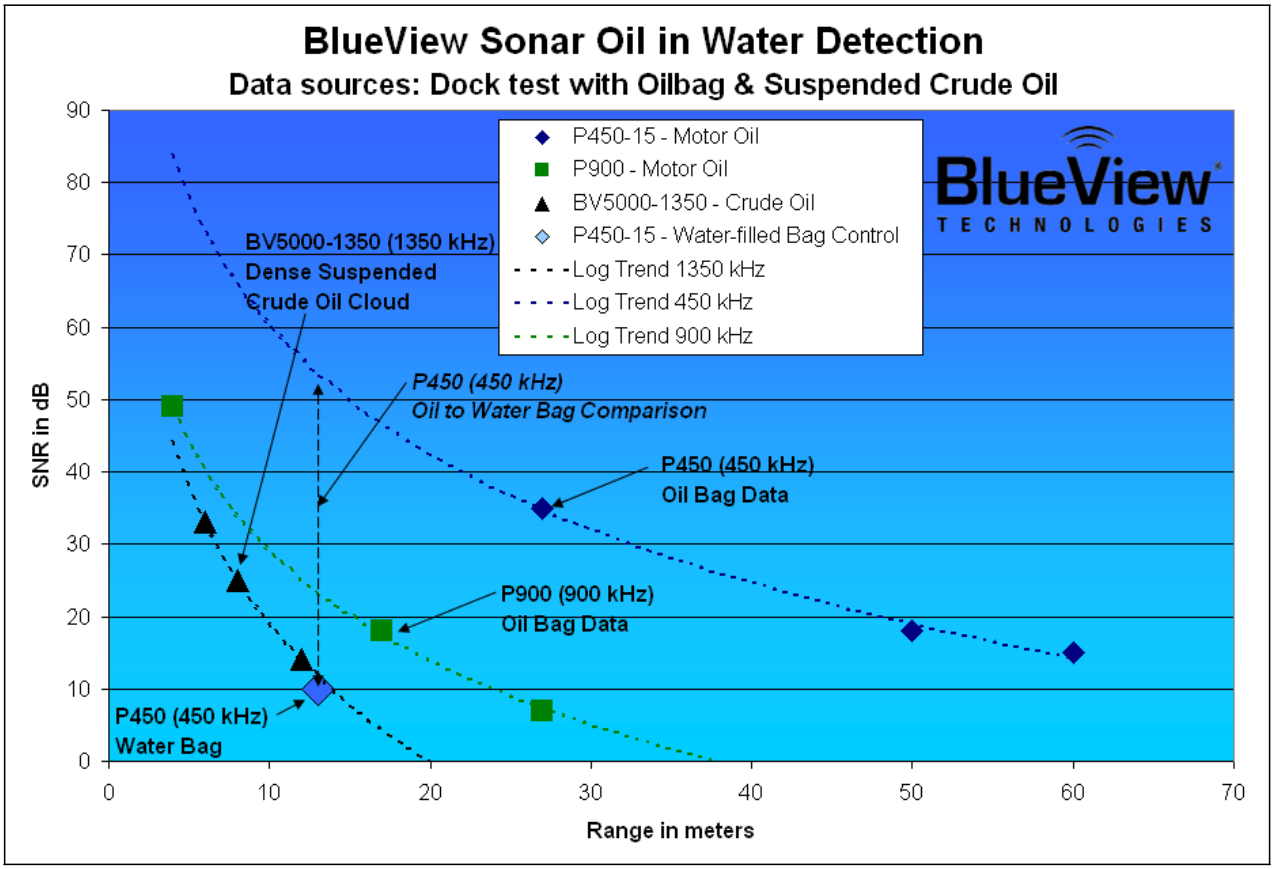

Figure 10. Signal strength of acoustic returns on suspended oil filled bags.

Detection of Heat Plumes

Though the test was completed as per the original procedure, flaws that were only partially through the insulation had no measureable effect on the overall convection of heat from the metal casing to the water. While this proved that the subsea insulation was extremely effective in this case, it also meant that the results presented below are from insulation flaws that completely penetrated the insulation. Additionally, as per procedure, sonar scans were completed both statically and dynamically. However, the dynamic scans are not included in this report as they vary with time which is difficult to convey with static image s in a report format.

As expected, small amounts of damage to the insulation – such as the ½-inch drill bit hole seen in Figure 11 – did not create a significant temperature change or density

difference in the water immediately outside of the defect. Though inside the hole there was a 4° F temperature differential, immediately outside the hole the temperature differential was less than 1° F. The amount of heat generated was simply not significant enough to generate the density difference required for a heat plume to be detectable by the BlueView sonar, as seen in Figure 12. The dynamic scan completed also showed no evidence of a heat plume.

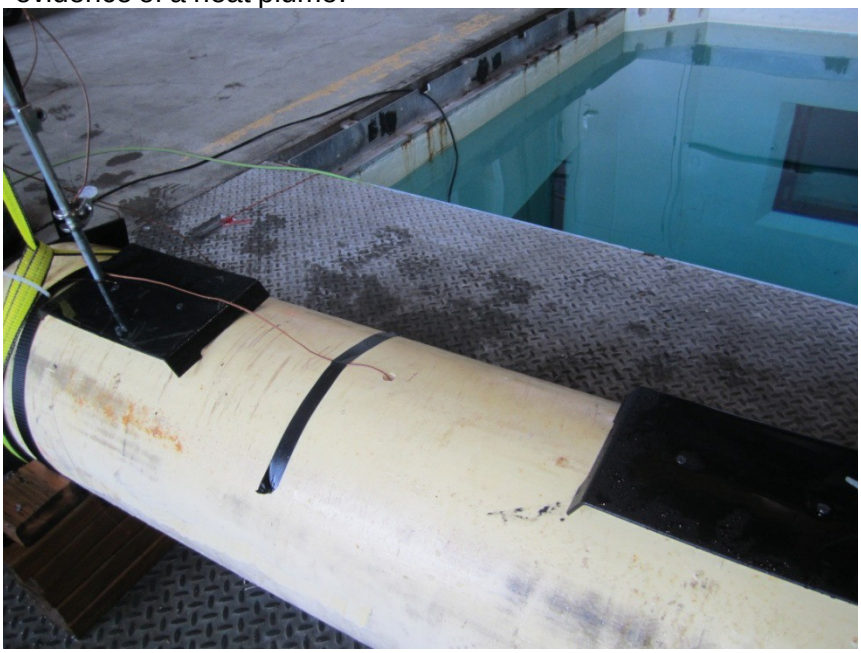

Figure 11. This is a photo taken of the ½" drill bit hole, the first defect introduced.

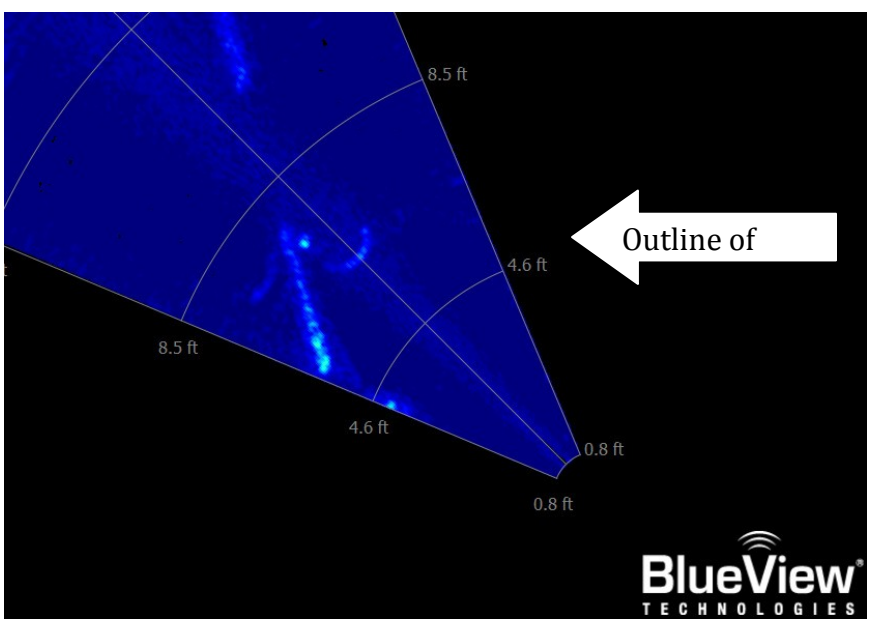

Figure 12. A sonar scan of the ½" hole, showing no sign of a heat plume.

For the slot defect, seen in Figure 13, similar results to the ½-inch hole were seen. The temperature differential outside the defect was once again less than 1° F, and

the sonar did not display any sign of convection, as seen in Figure 14. The dynamic scan completed also showed no evidence of a heat plume.

Figure 13. This image shows the slot defect, simulating a crack in the insulation.

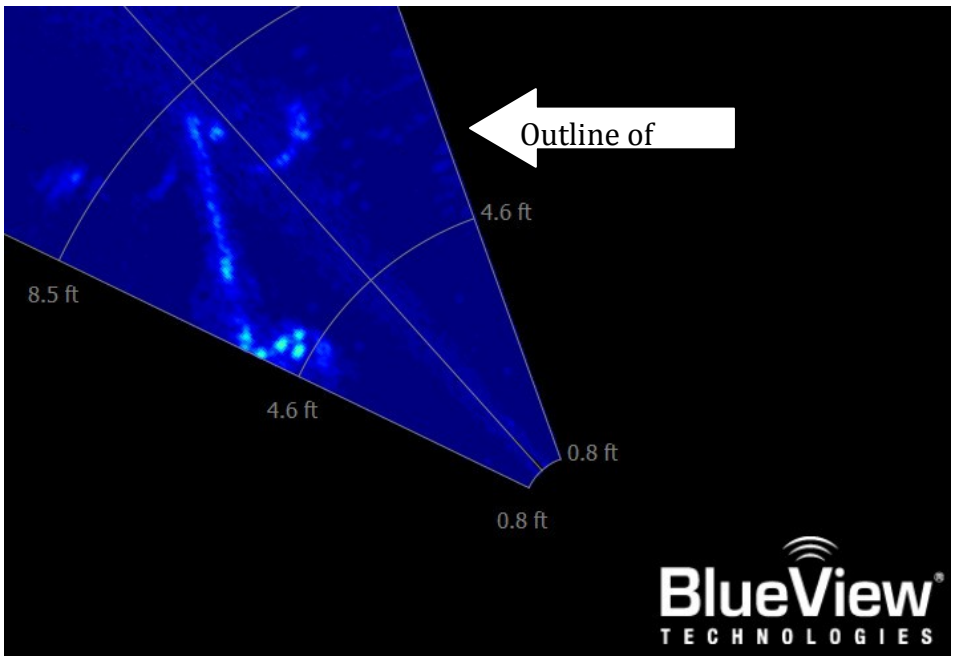

Figure 14. This sonar scan of the full depth slot once again shows no evidence of a heat plume.

Next, the 10 in^2 and 20 in^2 holes, seen in Figure 15 and Figure 16 below, were tested. There was some evidence of convection in the close-range sonar test, though no evidence in the 7-foot static scan, or in the dynamic scans. This slight evidence can be seen in Figure 17.

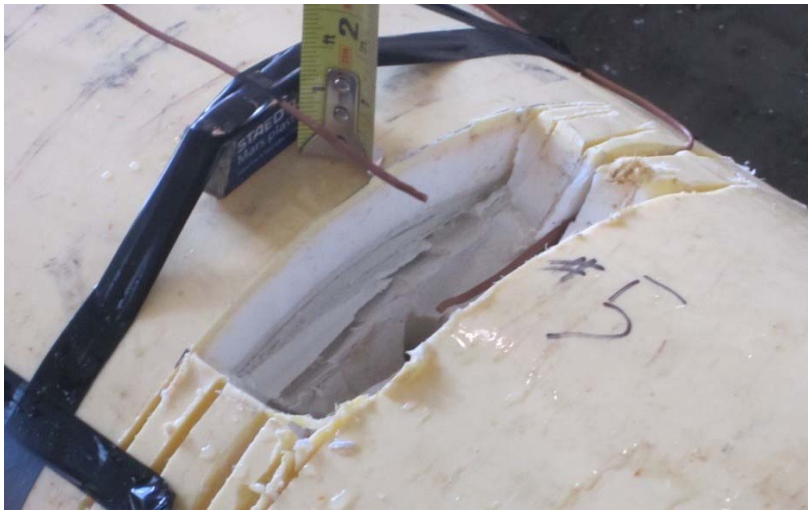

Figure 15.This image shows the 10 in^2 hole created in the pipe.

Figure 16. This camera image shows the size of the largest flaw, 20 in^2, introduced in the pipe.

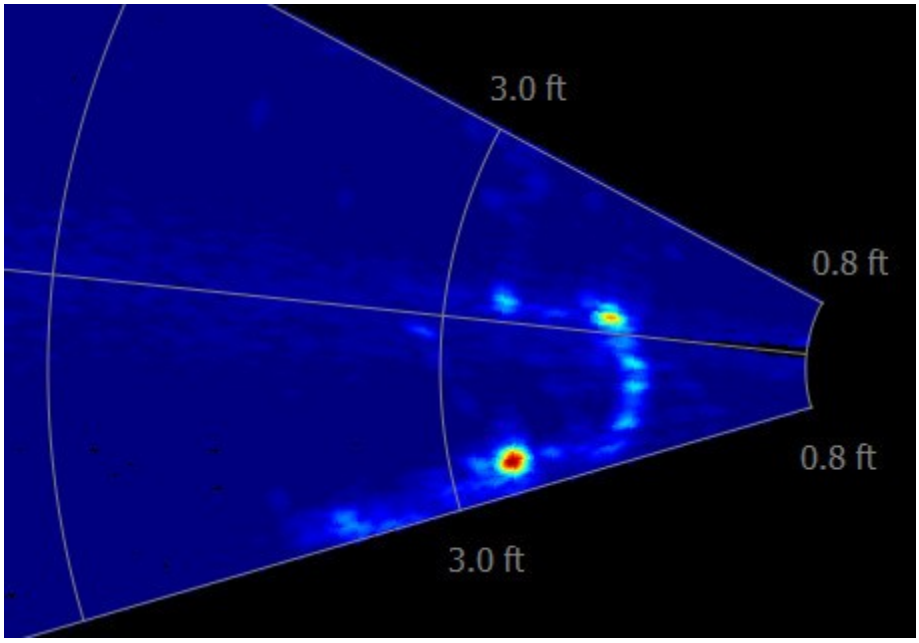

Figure 17. This image shows the close-range sonar output of 10 in^2 flaw scan, showing slight evidence of convection.

Ultimately, it was determined that there is still work to be done by BlueView to detect heat plumes in an offshore environment. Though there was subtle evidence of convection present in the close-range amplitude imagery, static sonar output for the large – 10 in^2 and 20 in^2 – defects, there was no evidence of convection in the other sonar scans. Additionally, this evidence of convection was fairly difficult to spot on the sonar output, so a different data processing mechanism would be required for operator use.

While the sensor technology is not ready for immediate offshore testing for pipeline heat plume detection, BlueView continues to explore potentially more effective ways that the sonar data gathered in this test could be processed and other sensor technology that could be used.

Impact to Producers

The techniques developed and tested under this project should significantly decrease time on-site for several underwater inspection and monitoring operations. These tools can also create a much safer environment by providing flexible inspection tools that can be deployed through the life cycle of a project and provide near continuous updates.

Technology Transfer Efforts

Papers concerning BlueView's RPSEA related work were presented at several industry related events and journals. The following presentations were made at the following meetings:

"New 3D Acoustic Scanning Tools and Techniques for Underwater Metrology and Inspection" presented in-person by Lee Thompson at the Offshore Technology Conference, Houston in 2011

"New 2D and 3D Acoustic Tools and Techniques for Underwater Metrology and Inspection" presented in-person by Lee Thompson at the Offshore Technology Conference, Houston in 2011

"High-Definition 3D Tools For Underwater Surveying and Inspection
High-Resolution 3D Scanning Sonar System Allows Rapid 3D Survey of Underwater Structures and Objects" printed in Sea Technology Magazine June 2012. Authors Lee Thompson and Art J. Schroeder

Conclusions

Improved techniques for underwater survey and inspection have been developed and shown to reduce costs and improve efficiencies in offshore oil and gas operations. Improved tools that provide analogous results to 2D optical video cameras and 3D optical laser systems, but are independent of water clarity are now being successfully deployed in a variety of oil and gas operations. The feasibility of leveraging the increased sensitivity and fidelity of these new instruments has been validated with encouraging results in both controlled testing and offshore operations. BlueView and Chevron Energy Technology Company are jointly pursuing continued testing and development as part of the RPSEA project and other efforts to continue to leverage and mature these technologies for high value offshore energy applications.

While the sensor technology did not show as promising results related to heat loss quantification, BlueView does believe that additional processing can be completed on the data gathered to make the sensor a viable alternative for heat plume detection. One proposed method is to use a Doppler map to make the slight signs of convection more visible to an operator. Additionally, there is a good possibility that future sensors will offer increased sensitivity and may be more useful for this application.

Recommendations

Use of acoustic based 3D scanners proved very successful for several underwater measurement and inspection operations. These positive results illustrate that a similar focus placed on other high value applications such as sonar-based ROV dynamic positioning, enhanced pipeline survey, enhanced storm damage assessment, and early detection of problem pipeline areas can deliver comparably rapid maturation. Further work should also include the additional use and testing of short range ultra-high resolution laser based systems to augment the current acoustic based techniques.

REFERENCES

None

LIST OF ACRONYMS AND ABBREVIATIONS

AUV	Autonomous Underwater Vehicle
OTC	Offshore Technology Conference
ROV	Remotely Operated Vehicle
NATO	North Atlantic Treaty Organization
DoD	Department of Defense
ONR	Office of Naval Research
UDW	Ultra-Deep Water
UW	University of Washington
DARPA	Defense Advanced Research Projects Agency
PMS-EOD	Program Manager, Explosive Ordnance Disposal
PMS-NSW	Program Manager, Naval Special Warfare
NOAA	National Oceanic and Atmospheric Administration
CAD	Computer Aided Design
DP	Dynamic Positioning
TRL	Technology Readiness Level