Final Report to

RPSEA

Research Partnership to Secure Energy for America

High Resolution 3D Laser Imaging for Inspection, Maintenance, Repair, and Operations

09121.3300.06.Final

Contract: 09121-3300-06

December 12, 2014

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1 ABSTRACT

In January 2011, 3D at Depth was awarded a RPSEA contract to bring high-resolution three-dimensional (3D) laser imaging technology from the lab into the subsea environment for the oil and gas industry. The project team included a working group from the offshore oil majors, subsea construction and survey companies, and a subsea sensor manufacturer. During the three year Phase 2, the project demonstrated the feasibility of utilizing high resolution laser detection and ranging (LADAR) in a subsea environment. The project also demonstrated the application of the system to support subsea metrology, vibration measurement and motion compensated field mapping.

3D laser imaging is a powerful data collection system that provides 3-D information for a specific area of interest. It is the predominate technology for terrestrial survey, construction, as-built analysis, and large-scale retro-fits. The 3D laser imaging market is a mature multi-billion dollar industry with an eco-system of software, expertise, and best practices. Developing the technology to provide high-definition subsea laser imaging enables the deepwater industry to use the current state of the art in 3D laser scanning and the related best practices developed for the terrestrial market.

Terrestrial laser scanners commonly produce centimeter spatial and range accuracy at several hundred meter range. Due to the absorption of water, realizable deepwater systems are limited to tens of meters range depending on the target and water conditions. ***To our knowledge, this RPSEA program enabled a world's first validation of underwater LADAR with sub-cm measurement accuracy at greater than 40m range***.

Results from the Phase 1 were reported in *High Resolution 3D Laser Imaging for Inspection, Maintenance, Repair, and Operations – Phase 1 Final Report.* The Phase 1 report discusses the theoretical background of underwater laser sensing, the first prototype sensor, the first pool test on a tripod, the first ROV tank trial, and reliability testing.

Phase 2 focused on the application of the system. Results from the first subsea laser metrology project are included that demonstrated the viability of the system to collect the measurements required to fabricate spool pieces in a subsea construction scenario. The latter part of the project then concentrated on applying the technology to data collection from a moving ROV and for remote vibration measurements.

A lack of highly accurate 3D data results in either higher risks or higher costs to build and maintain environmentally safe production and product transportation systems. The speed and precision of the technology developed by this project reduces operating costs for underwater inspection, maintenance, and repair; reduces environmental risk through more accurate inspection; and significantly improves construction quality/reliability through rapid access to sharable survey-quality as-built data before, during and after construction.

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4 EXECUTIVE SUMMARY

3D laser scanning, or LiDAR, is the predominate technology for terrestrial survey, construction, as-built analysis, and large-scale retro-fits. Using a patented technology, 3D at Depth has successfully developed a subsea LiDAR system with performance comparable to its terrestrial counterpart. Through this RPSEA funded project, the team extended the technology beyond the lab environment, developed a working prototype, and now has a commercially available system called the SL1. The project showcases RPSEA's ability to accelerate the development, adoption and commercialization of new technologies for the energy industry. Through RPSEA's focused project management and effective private and public partnerships, the project has led to the development of a new industry segment called subsea LiDAR which has redefined many subsea measurement processes and is rapidly being adopted across the globe.

3D at Depth had proven the ability to collect 3D data in an underwater tank in early 2009. The laboratory results provided a basis for a fully self-contained sensor which could be deployed subsea at depths up to 3000m on a ROV. Using an iterative design and testing plan, the team successfully performed two open water trials in 2013. In March of 2013, the first deepwater trial validated the ability of the system to perform at depth while operating from a ROV. The system was integrated with a Perry XL ROV and brought to a depth of 3290 feet a total of 12 times and collected high resolution 3D images of a PLET. This milestone demonstrated the system's ability to perform in the Ultra DeepWater (UDW) environment.

The second trial sought to validate the accuracy of the system for performing spool piece metrologies. The spool piece metrology process was determined by the RPSEA working project group to be the highest value initial application for the system with the potential to save significant vessel time and offer high value derivative data to enhance risk management and life of field processes. The demonstration was held at the Ohmsett facility in April 2013 using their 600 foot long salt water tank. The demonstration included performing several measurement scenarios between two flanges at ranges up to 35 meters. Using high accuracy land based surveying tools as a baseline, the demonstration concluded that the subsea LiDAR system's accuracy was comparable to land based laser scanners and could provide the accuracy needed to perform spool piece metrologies while collecting full as-built models of the assets to support longer-term life of field applications.

In February of 2014, the system successfully performed 13 metrologies in the Gulf of Mexico (GoM). The initial four metrologies were performed in conjunction with a traditional Long BaseLine (LBL) metrology and the results demonstrated that the system provided the accuracy required for spool piece fabrication. Once these initial four metrologies were validated, the system became the primary metrology method for the project and demonstrated significant time and cost savings to the overall project. The project also led to the first fully scanned subsea drill center, thus proving the utility of subsea LiDAR for capturing the as-built condition of assets leading to enhanced management and improved risk management and assessment capabilities.

The Working Project Group recommended that the team validate the integration of the sensor with an inertial navigation system to determine if subsea LiDAR would support a moving platform such as an Autonomous Underwater Vehicle (AUV) or ROV. Since the accuracies and stability of the sensor was proven during field demonstrations, the ability to collect high resolution 3D data for pipelines and seabed mapping was a logical next step. As a first step, the team validated that is was possible to achieve +/- 1cm accuracy while manually moving the sensor and navigation system in a basic laboratory environment.

3D at Depth was given the opportunity to team with Monterey Bay Aquarium Research Institute (MBARI) to perform sea bed mapping from their moving ROV platform at depths of greater than 9000 feet. Two such missions were performed, one in December of 2013, and again in May of 2014. Both missions were highly successful and resulted in 3D subsea ladar images of clam beds stitched together using the ROV navigation data.

In response to feedback item from the Working Project Group, the Field of View (FoV) of the SL1 system was increased. The base SL1 system has a 30° x 30° FoV. The system can be mounted on a pan stage to enable a 360° coverage in azimuth. The SL1 system was redesigned into a two-housing system to enable mounting on a pan/tilt stage to further increase the effective FoV of the system to 360° in azimuth x 130° in elevation. An open water trial of this two-housing system mounted on a pan/tilt stage was performed in November 2014 in the GoM. The system successfully collected point cloud data of a flex joint that the SL1 system would not have been able to collect.

As a final task, the team quantitatively demonstrated the versatility of the system by measuring the frequency and range displacement of a vibrating target at greater than 8m range underwater. A range displacement sensitivity of better than +/-5mm was demonstrated for a frequency range of 2Hz to 15Hz.

There were two significant outcomes of the project. First, from a technical perspective, the use of subsea LiDAR to enhance measurement and asset management was proven in real world conditions. The second outcome was the effectiveness of the RPSEA program in bringing new technologies to market rapidly in an effective private/public partnership.

In 2011, subsea laser scanning was a concept which was proven in a lab environment. With the support of RPSEA and the working group of industry leaders, subsea laser scanning has become a viable commercial capability in three years. The technology has been successfully used on more than 20 projects worldwide and represents a new capability for asset integrity, measurement, and general life of field applications.

3D at Depth wishes to acknowledge the support of Technip, BP, and the other Working Project Group members whose shared vision and hard work helped bring this new capability to the industry.

5 INTRODUCTION

A critical area for effective construction and asset management operations is quality. Quality in manufacturing leads to more consistency, less down time and lower repair costs. This is significant when the assets are generating millions of dollars per day. One of the cornerstones of quality in construction and asset management is measurement and survey. Accurate surveying leads to more precise construction, and more accurate inspection reduces costly down time by finding issues that were previously unattainable or before they increase in consequential risk. A lack of accurate data results in higher risks or costs to build and maintain environmentally safe production and product transportation systems. Better measurements equates to better management.

Subsea construction, inspection and maintenance processes and their associated technologies have not kept pace with their land based counterparts. On land, the survey and measurement industry was transformed by the introduction of 3D laser scanning technologies. The laser scanning market is a mature, multi-billion dollar industry with an eco-system of hardware, software, expertise and best practices. 3D laser scanners quickly produce precise, high resolution 3D models of as-built facilities and are used throughout the construction and maintenance process.

Conversely, the technologies for undersea surveying and measurement are relatively coarse and include two main technologies: video and SONAR. Video provides a method for visually inspecting assets but does not provide quantitative information – only 2D information. Attempts have been made to acquire 3D data underwater with cameras using methods such as photogrammetry and stereo imaging.[i,ii,iii] Major limitations with these approaches are reconstructions in areas of low textural information, poor image contrast due to water conditions, and shadowing due to directional lighting. [iv]

SONAR systems have been the main tools for measurement and survey for many years and have become very sophisticated. Many companies have developed high resolution multi-beam sonar systems which can produce angular resolutions as small as 0.2°. However, the resolution of these systems are fundamentally limited due to the underlying physics – the wavelength of light is over 10^8 times smaller than ultrasonic wavelengths and can achieve angular resolutions of less than 100µrad (0.006°). Therefore, light based sensors inherently have higher spatial resolutions than sonar systems.

Multiple underwater systems have been developed in the past to take advantage of the high resolutions achievable with lasers. A literature search reveals that both triangulation and range gated (or Time of Flight) underwater systems have been investigated over the last several decades.

Laboratory versions of triangulation based laser imagers for clear water and short range (0.2 – 0.4m) were developed and demonstrated since the mid-1990s.[v,vi, vii,viii] Even at that time, triangulation systems were noted for providing high resolution at close range (less than 3m), while range-gated systems could provide better resolution at longer ranges.

A triangulation based system was developed by K. Moore at the Scripps Institute of Oceanography in 2000 for bathymetry.[ix] This system was designed to provide approximately 3mm accuracy depth information at 2m range that degraded exponentially with range. Depth resolution errors would approach 10cm at 10m range.

More recently, another triangulation system was developed for seafloor roughness measurements. This system operated approximately 75 centimeters above the seabed and produced approximately 0.3mm(x) x 0.5mm(y) x 0.3mm (depth) resolutions while deployed off the New Jersey coast.[x] Note that the range is generally less than 3m for these triangulation systems. This is a fundamental limitation of the triangulation method for calculating range, and thus limits its usefulness as a general underwater survey tool.

Many of the terrestrial laser imagers available on the market today are based on Time of Flight (ToF) technology. This includes products such as the Leica ScanStation C10, the Trimble CX Scanner, and the Optech ILRIS-3D. These ToF sensors use a laser to emit a pulse of light. An accurate timer is used to time how long it takes for the pulse of light to travel to and from a target. This time is then used to calculate the range to the target based upon the speed of light. There is no fundamental limitation on the range of a ToF sensor besides the ability to detect the return photons reflected off the target (ToF ladars are used to measure the distance to satellites). Therefore, highly reflective objects can be detected at longer ranges than low reflectivity targets.

A literature search will reveal that scanning, pulsed, 3D laser imagers have been investigated and deployed underwater over the last couple of decades for military purposes[xi,xii,xiii,xiv]. Some of these are underwater based and others are aircraft based to detect underwater mines. In either case, these systems did not attempt to achieve the range and spatial accuracies provided by current terrestrial laser scanners (sub-inch).

The underwater 3D laser sensor developed under this RPSEA contract has the fundamental advantage of providing sub-centimeter precision at greater than a 45m range, a capability that to the authors' knowledge has not been previously demonstrated.

This final report documents the development of the underwater laser scanning system over the last 3 years by 3D at Depth under Phase 2 of the RPSEA program. The first section walks through the tasks outlined in the statement of work and the results of each task, including open water trial results. The second section directly addresses the impact of this project and the resulting commercial product on the producer community. The third section discusses the technology transfer activities for the program, which is a key component of the RPSEA project charter.

6 STATEMENT OF WORK

This section reports on the individual tasks from the Statement of Work, including the results of the open water trials.

6.1 Task 3.0 – Field Asset Monitor & Inspection – System Update and Static Open Water Trial

The goal of this task was to take the full scale prototype hardware developed in Phase 1 on an open-water technology trial. As the system was not integrated with the navigation system at this time, this trial performed laser scans of various assets from a stationary platform at an open water location. The successful completion of this task demonstrated the base technology capability to acquire high-resolution data from a stationary platform in an open water environment. This task included four sub-tasks.

6.1.1 Identify an open-water trial of opportunity and develop the concept of operations

An open water trial of opportunity was identified with Technip in the Gulf of Mexico in early 2013. As a cost share partner, Technip provided vessel time as well as project management and operations resources. The goal of this test was to:

- Validate the operational capability of the sensor at depth
- Integrate with ROV communications and power
- Control the scanner remotely
- Acquire point clouds of subsea assets

The demonstration leveraged an existing project on the Normand Commander, a 92.9 m DP2 Multi Service Vessel. As a non-critical path task, the team was relegated to perform the trial during project operations which did not require the use of the XLX ROV. The primary function of the project at that time was the installation of jumpers. Prior to the offshore demonstration, the 3D at Depth personnel were required to complete the BOSEIT training for offshore safety.

6.1.2 Update the system from any lessons-learned in the ROV tank tests at the end of Phase 1

Based on the results of the ROV tank tests in Phase 1, 3D at Depth implemented several upgrades to the system prior to the open water trial.

- Upgraded the laser from a pulse rate of 20 kHz to 40 kHz which improved the speed of collection
- Updated the optical bench for a more robust design that also enabled a shorter housing
- Upgraded to a smaller yet more sensitive receiver
- Updated internal triggering circuitry
- Upgraded subsea cables and bulkhead connectors for more reliable Ethernet communications
- Upgraded the power board for more reliable operation
- Upgraded internal wiring for improved reliability and serviceability
- Implemented multiple gain settings to enable a wider range of operating environments
- Implemented a Class 1 laser mode of operation
- Enhanced the software subsystems for data collection and processing of point clouds from the sensor's RAW data formats.

6.1.3 Integration with industry standard post processing products

One of the goals of the project, and for the development of the subsea LiDAR capability, is the ability to leverage the best practices and tools from the topside laser scanning market. The topside laser scanning market is a mature industry with a global ecosystem of hardware, software and service providers. Point cloud processing has become an established discipline where technicians can derive 3D models from scanned data. These technicians use a variety of tools for this work with Leica's Cyclone™ as the market leader.

To accelerate the adoption of subsea LiDAR, the team realized the importance of providing a dataset which can be easily adopted by the existing point cloud processing community. The LASer or LAS was selected as the primary data output from the SL1 system. This format was developed by an open community managed by the American Society of Photogrammetry and Remote Sensing (ASPRS, 2014).

"The LAS file format is a public file format for the interchange of 3-dimensional point cloud data between data users. Although developed primarily for exchange of lidar point cloud data, this format supports the exchange of any 3-dimensional x, y, and z tuplet. This binary file format is an alternative to proprietary systems or a generic ASCII file interchange system used by many companies. The problem with proprietary systems is obvious in that data cannot be easily taken from one system to another. There are two major problems with the ASCII file interchange. The first problem is performance because the reading and interpretation of ASCII elevation data can be very slow and the file size can be extremely large, even for small amounts of data. The second problem is that all information specific to the lidar data is lost. The LAS file format is a binary file format that maintains information specific to the lidar nature of the data while not being overly complex."

With LAS as the standard output format, the team leveraged Cyclone for post processing the point clouds into specific measurements and CAD models. As an example of the Cyclone processing, a dataset is shown below that was implemented after the first open water trial.

Since the SL1 has a 30° x 30° swath, the unit was equipped with a PAN motor which rotates the unit. In order to collect a wide field of view suitable for metrology or other field mapping applications, the unit needs to scan and then rotate. The resulting scans then need to be aggregated into a single point cloud with a single coordinate system. The 3D at Depth processing tool was modified to correct for the PAN angle so when imported into Cyclone, the dataset represents the full field of view.

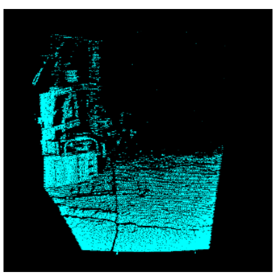


Figure 1: Single 30° x 30° scan

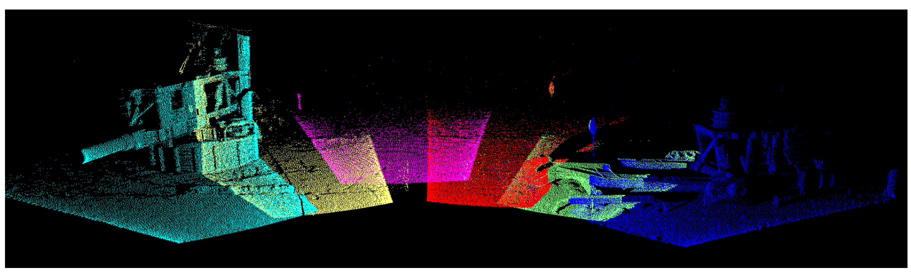


Figure 2: Six 30° x 30° scans, rotated at 20° PAN increments

6.1.4 Perform the open water trial and data processing

As planned, in March 2013, 3D at Depth and Technip completed the first open water trial of the subsea LiDAR unit in the Gulf of Mexico. The SL1 system was integrated to the XLX through direct power and communications cabling via a MacArtney Nexus IV MUX. As to not impact project operations, the SL1 was mounted on the rear of the ROV and although not the optimal location for data collection, this configuration was suitable for demonstrating the performance of the sensor.

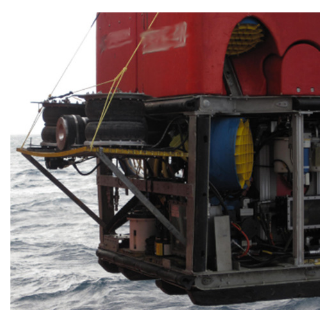


Figure 3: SL1 Integrated to an XLX ROV

The sensor was brought to a depth of 3290 feet 12 times although due to project constraints, the team was only able to collect two scans of a PLET. Since the objective was to validate the performance of the system at depth, the trial proved that the unit could function in its intended deepwater environment. Power and communications through 1000 m of ROV umbilical and tether was confirmed and the resulting scans provided an idea of the system capability for collecting high resolution point clouds at depth.

Figure 4: PLET and Jumpers at 3272 ft. depth

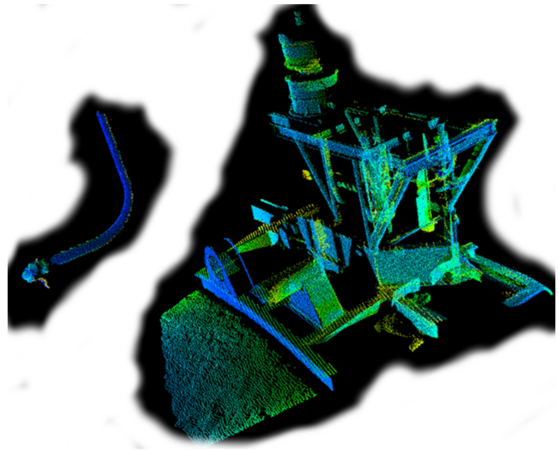


Figure 5: Resulting Point Clouds of the PLET

In March 2013, the subsea LiDAR had successful GoM offshore data collection at 1000m depth in non-ideal water clarity conditions at greater than 10m range.

6.2 Task 4.0 - Rapid Survey for Subsea Tieback – System Development & Tank Trial

The primary goal of this task was to bring a new capability to the hardware - precise, accurate survey capability. This technology development enables fast survey measurements needed for applications such as jumper length determination.

6.2.1 CONOPS development

Based on feedback from the working group, the initial application for the subsea laser scanning system was to be subsea metrology. Subsea metrology processes calculate the relative horizontal and vertical distances and relative pitch and roll angles between two hubs or flanges. These measurements are presented in a graphical format as a metrology report typically in AutoCAD or other CAD format and are used to fabricate and install the connecting spool pieces.

Often the connecting spool pieces are the final section of the pipeline network and therefore one of the final components in producing hydrocarbons. Although there are several methods for performing subsea metrology, operators and construction contractors are constantly trying to find methods to achieve first oil.

The initial thought for using subsea scanning for metrology was presented by Technip, a project cost share partner. Technip is the largest subsea construction company in the world and has a culture of implementing new technologies for their clients. The Technip team and the working group theorized that the use of subsea scanning as a metrology tool would provide significant cost and time savings and yield datasets which could be leveraged throughout the life of the field.

The International Marine Contractors Association publication S019, defines typical required metrology accuracies which formed a guideline for developing the metrology process for the subsea LiDAR application. (International Marine Contractors Association, 2012)

Point	X	Y	Z	Pitch	Roll	Heading
Unit	**mm**	**mm**	**mm**	**Degrees**	**Degrees**	**Degrees**
Hub to hub relative distances	50 to 150	50 to 150	50 to 150			
Hub to hub relative angles				0.5 to 1.0	0.5 to 1.0	0.5 to 2.0

Figure 6: Typical required metrology accuracies [IMCA S019 Metrology Guidance Document]

From a DOT paper published by Dave Matthews of Technip in 2014, the following drawing describes the measurements needed for a subsea metrology. (David A. Matthews, 2014)

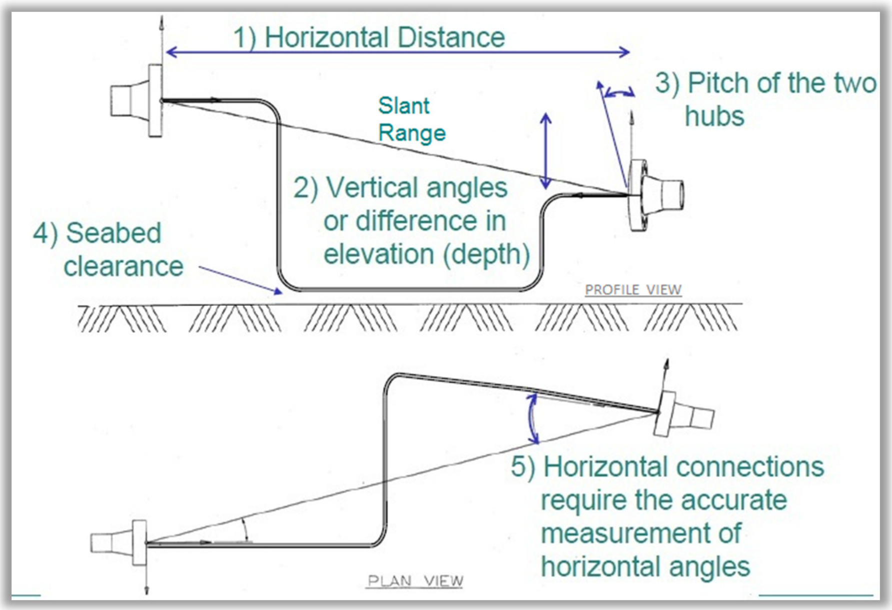


Figure 7: Measurements necessary for a horizontal spool metrology. Upper view is in profile, lower view is plan

Once the concepts were understood, the team developed a system for performing metrologies with the scanner and a methodology for comparing the accuracies with the current state of the art in topside surveying – a total station

The sensor was designed with a maximum subsea field of view of 30° x 30°. For metrology applications, typical distances are 100 feet, which exceed a single scan's range. For this reason, the team needed to rotate the sensor to collect a series of 30° x 30° scans which, when imported into the post processing tool, would yield a 180° x 30° field of view. If the range of the sensors was 50 feet, then a metrology could theoretically be completed by placing the sensor between the two structures and scan each hub while rotating about the Z axis.

This design required the integration of a PAN motor with a high resolution encoder. Fortunately, the team located several options on the commercial market and began to test these units. After extensive lab testing, the team settled on a commercial unit which met the accuracy requirements and could support the sensor at depth.

The next step was the development of a methodology for performing metrologies in turbid water conditions where the range did not allow for the collection in one placement of the scanner. The team researched the topside laser scanning market and identified commercially available high precision spheres – or omnidirectional targets. These spheres could be scanned from any direction and a centroid can be easily derived using Leica's Cyclone point cloud processing tool. The team realized that in order to register multiple scans together and meet the accuracy requirements of the IMCA standards, there should be a minimum of four coincident points for registering two scans together.

As a cost share partner and potential user of the SL1, Technip wanted to validate the SL1 sensor in a controlled environment to determine its applicability for survey and 3D data capture. The testing was performed from April 22-26, 2013 at the Ohmsett facility, in Leonardo, NJ - leveraging their 200m x 20m salt water tank.

The scope of the trial included performing tests to determine:

- The accuracy of the SL1 for simulated spool piece metrology processes measured against traditional land based survey methods; target accuracies included ±10 cm for point to point measurements and ±1° for heading measurements
- The processes for collecting and processing the resulting datasets in varying salt water conditions

The team consisted of members of CDL, 3D at Depth, UTEC Survey, and Technip. The tests were intended to validate the accuracy and overall operational effectiveness of the SL1 subsea LiDAR system for performing spool piece metrology. In addition to the SPM testing, the team also validated the system for seabed mapping and 3D data capture capabilities which are derivative products of the SPM processes.

6.2.2 Facility

Figure 8: The Ohmsett Test Facility in Leonardo NJ

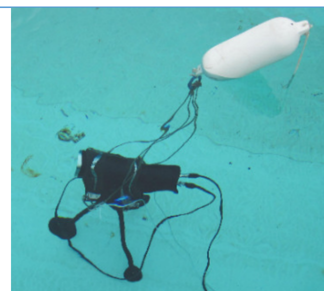
"The National Oil Spill Response Research & Renewable Energy Test Facility provides independent and objective performance testing of full-scale oil spill response equipment and marine renewable energy systems (wave energy conversion devices), and helps improve technologies through research and development. It is the largest outdoor saltwater wave/tow tank facility in North America and is the only facility where full-scale oil spill response equipment testing, research, and training can be conducted in a marine environment with oil under controlled environmental conditions (waves and oil types). With recent emphasis on developing renewable energy sources, Ohmsett's mission has expanded to offer a research and testing venue for wave energy conversion devices.

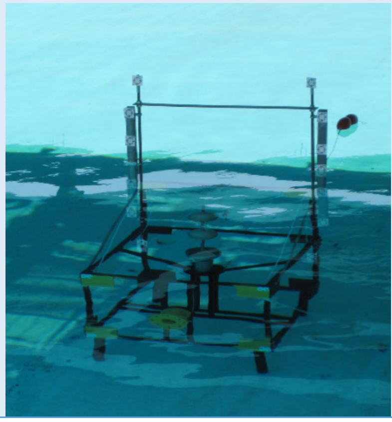
The facility, located an hour south of New York City, in Leonardo, New Jersey, is maintained and operated by the U.S. Department of Interior's Bureau of Safety and Environmental Enforcement (BSEE)." (Ohmsett About Us, 2013)

Technip leased the facility for the week, including the tow-bridge, shop, and associated facilities, to perform the SPM trials as part of their project cost share.

6.2.3 Equipment

The equipment used during the trials included the following:

SL1 Laser Scanner – rev. 1 (1x) • Shown on a tripod with integrated PAN unit • 360° x 30° field of view • Power and Ethernet communications supplied through AC external power source using a single Burton cable	
Registration targets (4 x) • 6" diameter precision aluminum spheres • Aluminum tripods Used to register scans together for larger scenes	

Custom Metrology Jig (2x) Developed specifically for SPM processes, the jig fits into a hub and can be quickly scanned to determine the distance and heading. The jig uses the 6” registration spheres.	
Test Cages for SPM (2x) These cages were dimensionally measured optically using several control points. When submerged in the tank, six points remain visible above the surface. These points are then surveyed using a total station while in the tank. The coincident scanning points include the spheres from the metrology jig – used for vertical flange alignment and the horizontal flange which will be scanned directly by the SL1. The centroids of the two spheres are used as control points for distance and heading. The center of the flange is used for distance and heading. The two cages are placed at various positions in the tank and then surveyed and scanned. The survey measurements were then compared with the SL1 derived measurements of distance and heading for the two flanges.	 

Test Cage for Spatial Distance Test
The backside of one of the test cages were fitted with survey targets to validate the distance between targets at specific ranges.

The survey targets are off the shelf laser scanning targets purchased from an on line vendor.

Figure 9: Test Equipment for the Ohmsett Trial

6.2.4 Test 1 – range and spatial accuracy

The goal of this initial test was to determine the effect of range on distance measurements for an object (spatial measurements). A cage developed for the SPM validation tests was used for this trial. Four black and white survey targets were attached to the back of the cage, and the distances between the targets were measured using a standard tape measure. Additionally, survey spheres, developed by 3D at Depth for registration of multiple scans, were added to the cage to determine if the centroids could be determined at various ranges.

The sensor was placed in a static location facing one end of the tank. The cage with premeasured survey targets was then placed at various distances/ranges from the sensor and scanned. The resulting datasets were processed using Leica Cyclone to automatically identify the center of each target, and then measurements were taken from the resulting model. The automatic target detection takes advantage of the ability to measure the relative intensity of each point based in the reflectivity of the surface. The ability to measure intensity/reflectivity is unique to laser scanning and offers the ability to classify materials.

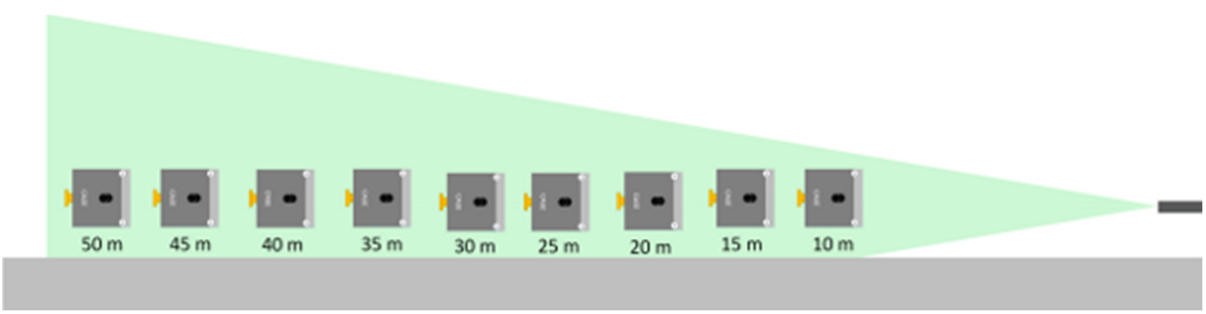


Figure 10: Planning Model for Test 1

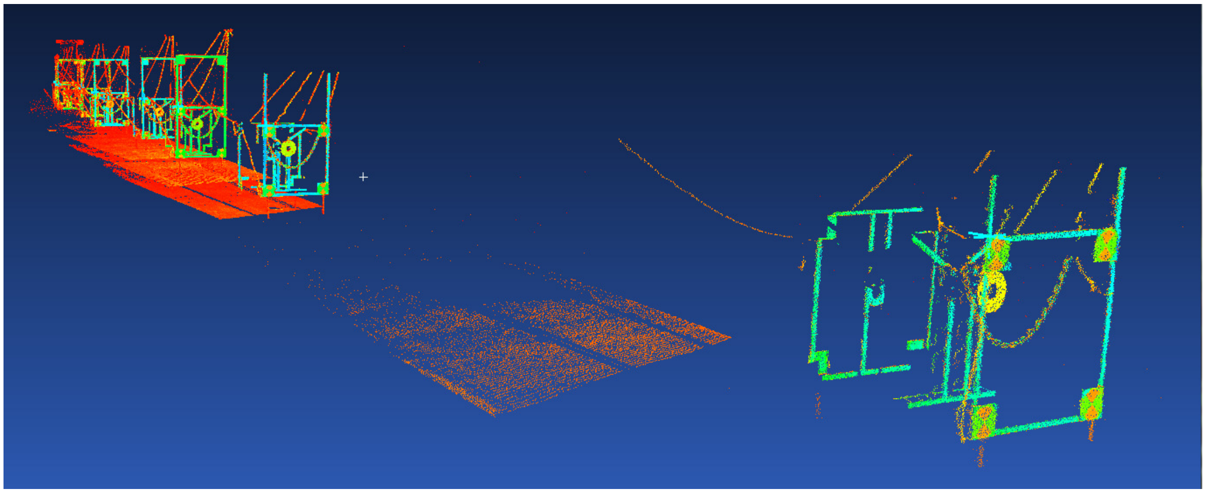
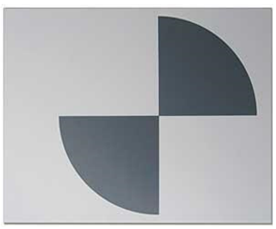
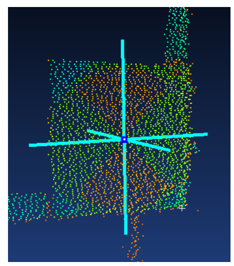


Figure 11: Resulting Scans for Test 1



Laser scanner target markers – used for topside laser surveys



Automatic Location of survey target center point using Leica Cyclone

Figure 12: Survey Targets and Resulting Scans

6.2.5 Analysis

The most accurate method for determining the center of the survey targets and spheres uses Cyclone's automatic target identification feature. At a range of 45 meters, the returns on the black part of the targets were minimal and therefore could not be used for target identification. At 50 meters, the spherical targets could not be accurately identified. This led to the conclusion that the sensor in clear water had a **maximum usable range of 45 meters**. However, the target frames were still visible at greater than 45 meters, still providing the user with target information, although it was less accurate. The spatial distances were not affected by range as the deltas in measured vs. scanned were similar regardless of range.

The use of standard black and white survey targets also provided a method for registering scans and setting control points on field assets. The ability to determine intensity/reflectivity is unique to laser scanning and allows operators to place targets on their assets for future as-built scans and define reference and control points.

6.2.6 Test 2 - survey accuracy testing for spool piece metrology

The next set of tests validated the accuracy of the SL1 for performing SPM operations. Two key scenarios were identified; one for poor visibility (range < 8 meters) and one for good visibility (range > 8 meters and < 20 meters). In some cases, the SL1 can capture both hubs in a SPM using one scanner location where the range is greater than 20m and in this case would not require registration targets.

In these tests, the two cages were placed at specific locations to simulate spool piece metrology configurations. A dimensional control survey was performed on the cages using a total station which captured a series of points on each cage. These observations were then used to measure the relative distance and heading between the flanges when placed in the tank. Once in the tank, the scanner was placed at varying locations to simulate laser metrology in poor and good visibility scenarios.

Figure 13: UTEC Survey conducting the dimensional control on the test cages

6.2.7 Analysis

The tank trials validated that in several configurations, the underwater scanner yielded measurement results well within the accuracy requirements for subsea metrology.

Two key scenarios were validated;

1) Good visibility where the scanner could scan both flanges from one location
2) Poor visibility where intermediate spheres were deployed between the two flanges and two scan positions were required to collect the required data.

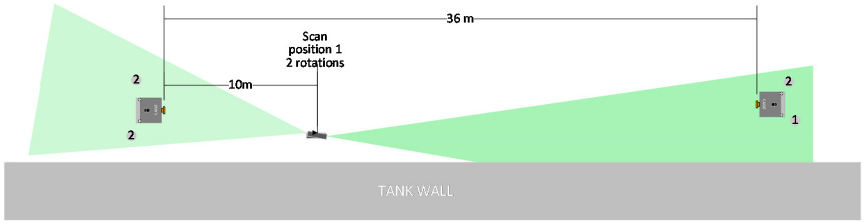


Figure 14: Scenario 1: Scanner between two flanges

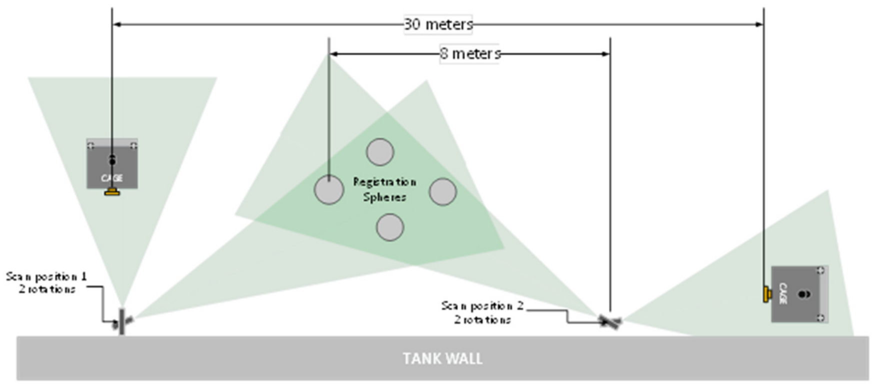


Figure 15: Scenario 2: Intermediate sphere targets and two scanner setups

The results validated that both setups could meet the accuracy requirements for spool piece metrology. ***Compared with the total station Dimensional Control (DC) results, the horizontal accuracies achieved were within millimeters in both scenarios.***

6.3 Task 5.0 – Field Asset Monitor & Inspection from Moving Platform – System Update & Tank Trial

The primary goal of Task 5 was to develop and implement a system that scans undersea assets from a moving ROV and creates 3D models. This task included four subtasks:

6.3.1 Develop the system to use the IMU data from the moving platform

The first subtask required the technology development of integrating IMU data from a moving platform with the laser scan data to produce a motion-corrected point cloud.

6.3.1.1 Indoor Navigation Sensor

Several development steps and controlled laboratory tests were conducted prior to data integration of the SL1 Sensor with an ROV Navigation system. Due to the complexity of the problem, an indoor, in air, navigation system was developed. This allowed for precise measurement and verification of the accuracy of the combined laser and motion data product. Stated differently, this custom Indoor Navigation System (iNAV) allowed for step by step integration and test providing detailed error and accuracy analysis between the laser sensor and the navigation system. This analysis proved essential to understanding of the final SL1 – ROV NAV output product.

The iNAV device consists of several low cost commercial sensors that are readily available, including line of sight distance sensors and a hobbyist Inertial Measurement Unit (IMU). The line of sight sensors are aligned along the three principal axes with known offsets to the center of rotation (COR) of the IMU. The iNAV sensor was then mounted to the front of the SL1 sensor, again, with known offsets as shown below.

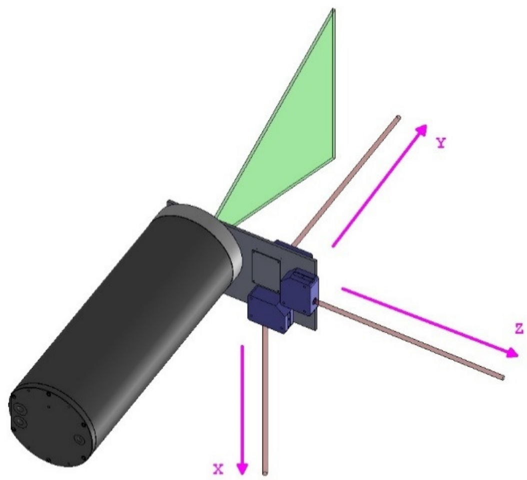


Figure 16: SL1 Motion Correction Setup

When used with three orthogonal surfaces, such as two walls and a floor, the iNAV software provides real-time output of a relative measurement of X, Y, Z and roll, pitch, and heading. These measurements directly correspond to outputs of an ROV Navigation device, thus providing an excellent development and test platform.

The tested accuracy of the iNAV device was approximately +/- 1.5 cm of orthogonal position, and +/- 0.25 degrees orientation, at a serial output rate of 5 Hz. Operation was limited to 5 minutes from calibration due to heading drift, and line of sight operation was limited to less than 30 degrees due to spot distortion. The iNAV device is shown below.

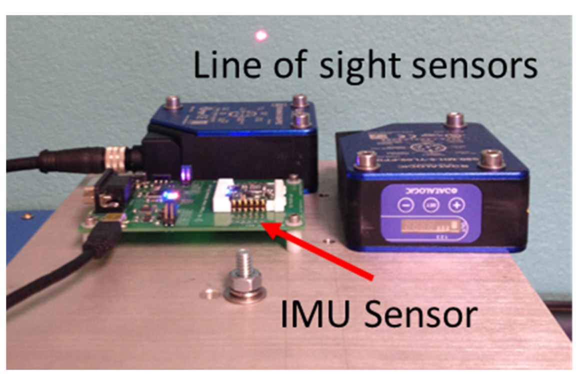


Figure 17: Internal and line of sight sensor setup

Interface software was written to communicate in real-time with the iNAV device and archive positional products with millisecond accurate timestamp. This software was executed directly on the SL1 sensor, thus greatly diminishing time stamp errors between the SL1 laser product and the iNAV positional product. Thus, utilizing the same clock for archive of both products, time stamp errors were tested and shown to be less than 5 milliseconds from the output of the serial devices in the iNAV.

6.3.1.2 SL1 and iNAV integration and test

An appropriate target was developed with asymmetries and measured with a tape measure to provide a basis for determination of accuracy. Some of the measured dimensions are shown in the Figure 18 below.

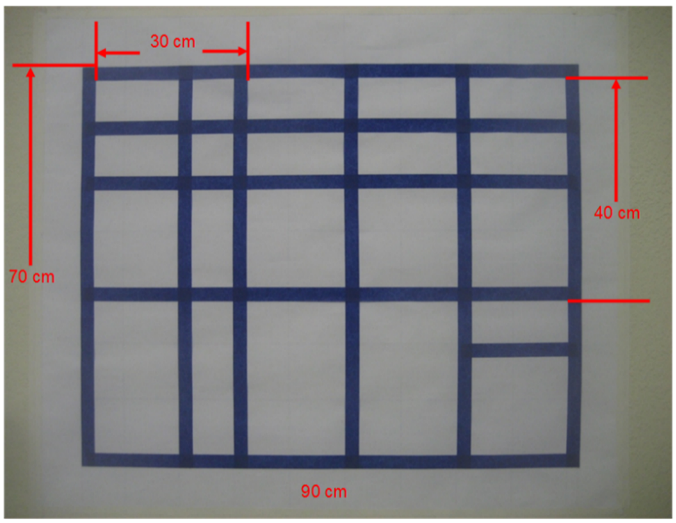


Figure 18: Laboratory Asymmetric Target

The SL1 and iNAV motion system were utilized in a series of motion tests to individually isolate deterministic motions. The SL1 and iNAV system were manually rotated, translated, or both around multiple axes while the laser was scanning. The resulting 3D point cloud was assembled using the iNAV data and the results were compared to the truth dimensions as shown in Figure 18.

6.3.1.3 Rotational motion tests

The first tests isolated rotation about an axis. The figure below is a screen shot of the 3D point cloud where color is mapped to intensity. For this test the laser performed a vertical line scan while the platform was manually rotate in Yaw or Heading, about the X axis (horizontally in this image). Distances between lines of the target were measured from the point cloud and compared to the truth measurements. The measurements and the delta from truth are shown in red in Figure 19. As can be seen below, the system achieved **less than +/- 1 cm error** when compared to actual target dimensions for iNAV angles of rotation less than 30 degrees. The rotation rate was less than 1 degree per second. The data collection period was about 60 seconds.

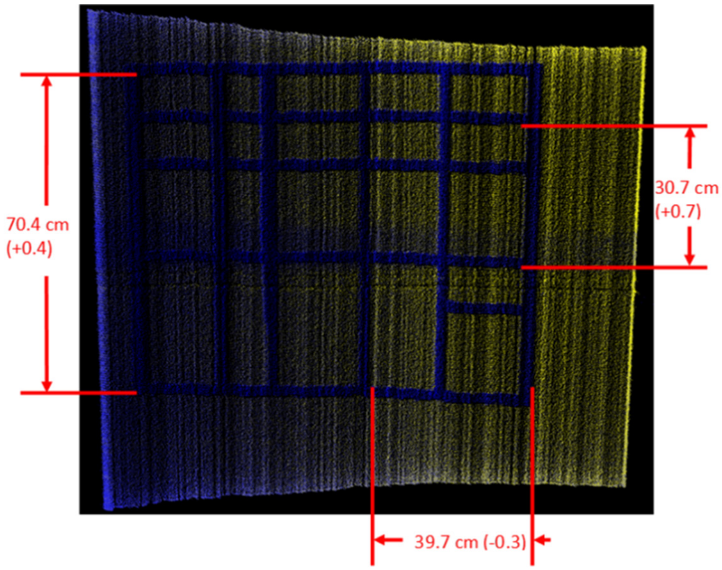


Figure 19: Rotational Axis Results – X Axis

Figure 20 shows the angles output from the iNAV system. The primary motion was a -40 degree rotation in Yaw.

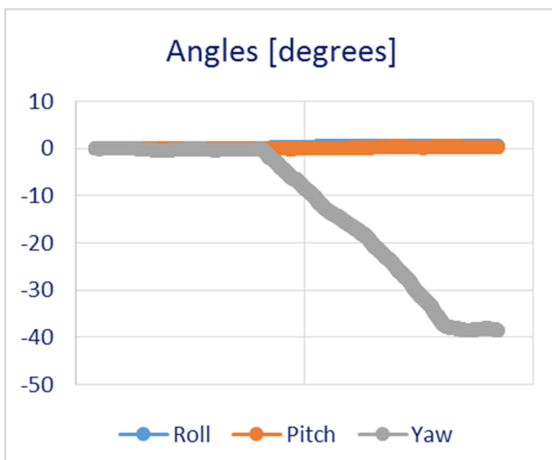
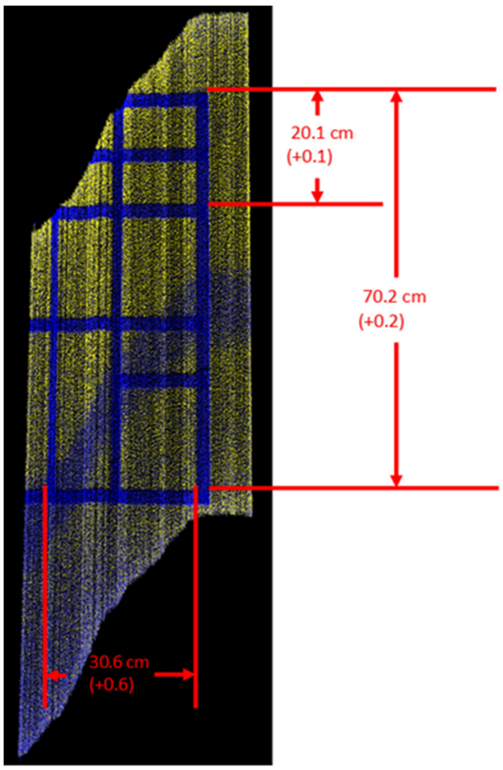


Figure 20: Angle of rotation (Yaw) as output from the iNAV sensor

Next was a dual axis rotation test about both X and Z axes. Figure 21 (Left) is a screen shot of the 3D point cloud where color is mapped to intensity. For this test the laser performed a vertical line scan while the platform was manually rotated in Yaw and Pitch (X and Z axes). Distances between lines of the target were measured from the point cloud and compared to the truth measurements. The measurements and the delta from truth are shown in red in Figure 21 (Left). As can be seen below, the system achieved **less than +/- 1 cm error** when compared to actual target dimensions. The platform rotations were taken over approximately 60 seconds.

Figure 21 (Right) shows the angles output from the iNAV system. The primary motions were -9 degrees in Yaw and -10 degrees in Pitch.



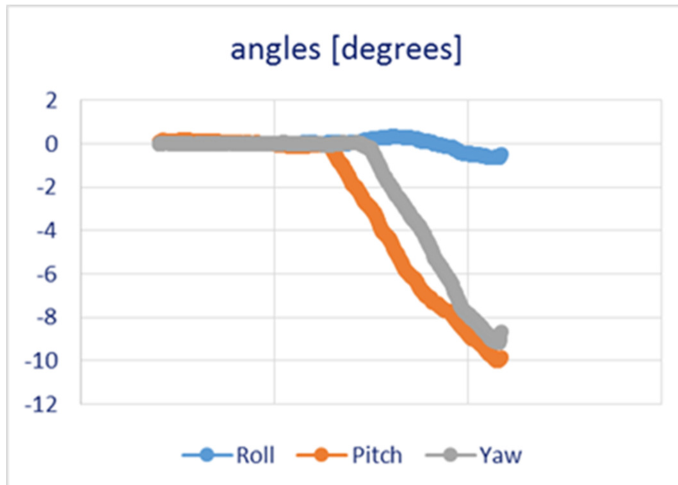


Figure 21: (Left) Screen shot of 3D point cloud from dual axes of rotation - X and Z. (Right) Output of iNAV angular motion

The final test involved a combination of Yaw rotation and translation in Y and Z. Figure 22 (Top) is a screen shot of the 3D point cloud where color is mapped to intensity. For this test the laser performed a vertical line scan while the platform was manually rotated in Yaw while manually translated in Y and Z. Distances between lines of the target were measured from the point cloud and compared to the truth measurements. The measurements and the delta from truth are shown in red in Figure 22 (Top). As can be seen below, the system primarily achieved less than +/- 1 cm error when compared to actual target dimensions. One measurement had 2.1cm error. The platform rotations were taken over approximately 60 seconds.

Figure 22 (Bottom) shows the angle and translational outputs from the iNAV system. The primary motions were -10 degrees in Yaw, 1.3m in Z and 2.5m in Y.

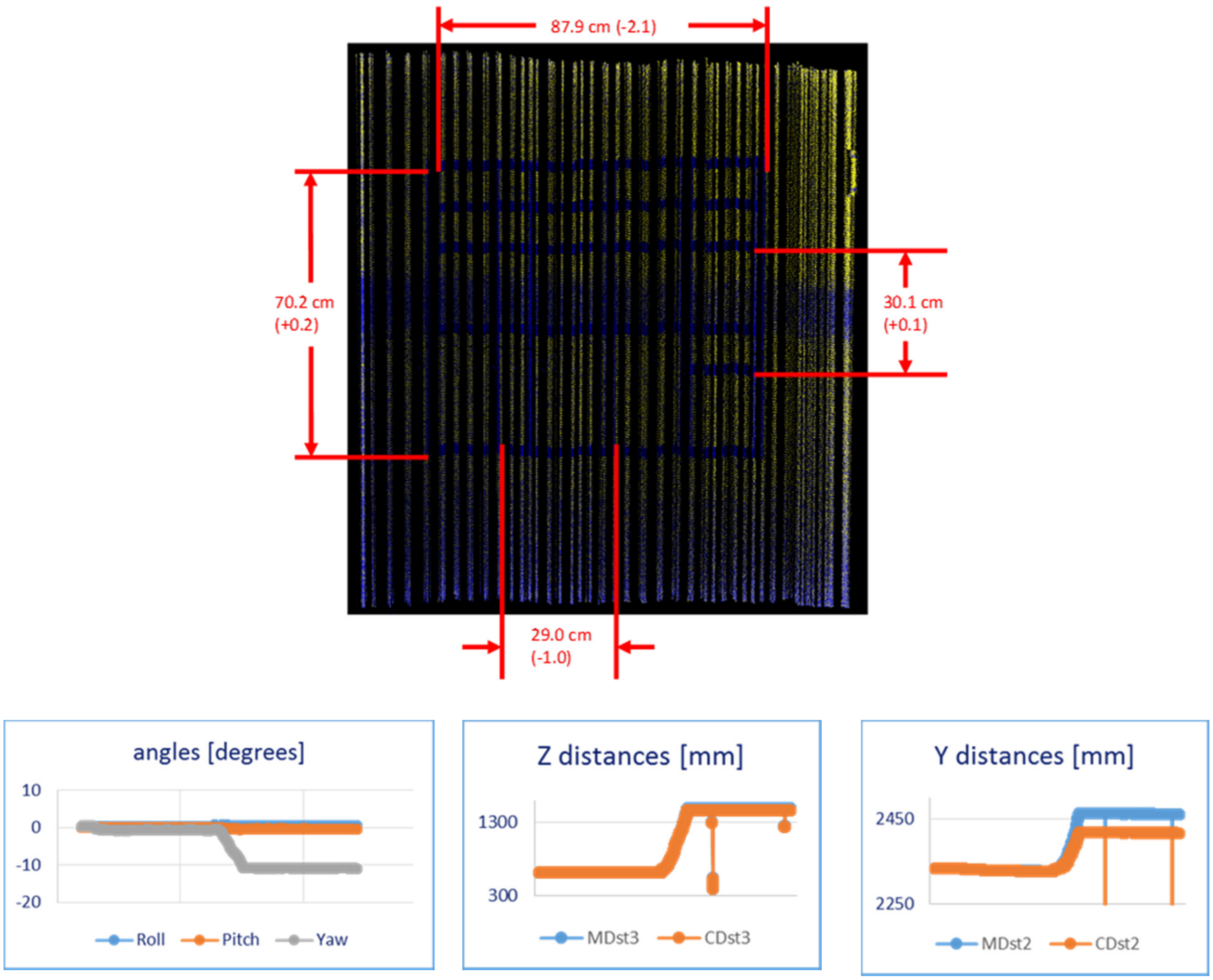


Figure 22: Results of translation in Y and Z while rotating in Yaw. (Top) Screen shot of 3D point cloud and errors from truth measurements (Bottom) Output of iNAV angular and translational motions

6.3.1.4 Analysis

In the lab, it was demonstrated that is it possible to motion correct the laser scan datasets based on the inertial information. The results showed a typical measurement capability of less than +/- 1 cm. One result showed an error up to 2.1cm. Replacing the land based sensors with DVL and INS systems may provide a capability to scan from a moving AUV or ROV while achieving accuracies which can support a variety of subsea applications.

6.3.2 Self-Calibration

With the goal of improving sensor performance, one subtask was dedicated to further develop the hardware to provide reliable underwater operation through improved calibrations. The successful transition of most products from lab prototype to commercial operation usually involves a series of calibrations to allow the product to operate within specification for all operational scenarios. This principle proved true for the SL1 sensor. Most importantly, several calibration methods were developed to ensure the sensor provides an accurate line-of-sight distance measurement for all operating water temperatures. Thus, if used in tropical or north Canadian waters, the sensor provides distance measurements within specification. To that end, a temperature compensation procedure was developed and validated to measure and record errors across all temperature ranges. Sensor specific calibration data was then utilized during normal operation to account for differences in ambient conditions to provide accurate measurements.

Additional calibration methods were also developed to provide pointing accuracy, as a result of slight manufacturing differences in the pointing hardware.

6.3.3 Increase the Field of View (FoV)

As pointed out by the working project group, the FoV of 30° x 30° was limiting for several applications. Therefore another subtask was dedicated to investigating different scanner and window configurations to increase the sensor FoV.

One method to increase the FoV is to increase the sensor's window size and increase the internal pointing mechanism's drive angles. While seemingly straight forward, both of these actions proved costly and greatly increased the size of the sensor. In short, as the window increases in size, the supporting endcap must also increase. This forces a larger wall diameter and an overall larger sensor. This same problem exists whether the window is mounted in the end cap or along the sensor tube. Additional complications result when trying to seal the circular, flat window into a curved tube. These again lead to an overall larger sensor and detracts from product usability and cost.

To overcome the above issues and provide an overall solution for viewing large swaths of targets, it was decided that repositioning the sensor was necessary. A commercial rotational pan unit was researched and chosen to meet the desired requirement. In this fashion, the sensor is mounted on top of the pan unit. Through a software interface in the sensor, the pan unit is then directed to a rotational position for each individual scan. The resulting data sets are then stitched together, armed with knowledge of the corresponding pan rotation angle. It should be noted that the pan unit accuracy adds to the overall error of the system for measurement of large data sets. The pan unit chosen provides a rotation accuracy of approximately 0.02°, resulting in a maximum error of about 3.5 mm at 10 meters.

In this fashion, the 30° x 30° internal sensor scan can be repositioned to collect a full 360° x 30° scan disk. This worked well for many applications, however it was discovered that more than 30° in elevation is also required for many applications.

An external pan/tilt component was located that allowed for over 130° in elevation FoV. Such a configuration is show below for an SL2 sensor mounted on a pan / tilt unit.

Figure 23: SL2 – Pan and Tilt Increases the Field of View

This configuration was successfully tested in open water in the GoM. Results are discussed in Section 6.4.5.

6.3.4 Integration with additional industry standard post processing products for moving platforms & integration with a ROV and test trial in a ROV test tank

Due to timing and the unavailability of ROV tank test opportunities, a tank test with a moving ROV was not performed. However, in its place, an opportunity arose in December of 2013 to mount the SL1 sensor on a ROV and perform laser scanning and data collection in open water. As part of the open water trial the data was integrated with additional standard post processing products for moving platforms.

See Section 6.4.3 for a complete discussion of the ROV integration, open water trial, and data processing with custom and industry standard post processing data products.

6.4 Task 6.0 – Field Asset Monitor & Inspection from Moving Platform – System Update & Open Water Trial

Task 6.0 completes Phase 2 with an open water technology trial of the upgraded 3D imager on a moving platform, an open water trial of survey data collection from a stationary platform, and an open water trial of the two housing sensor mounted on a pan-tilt stage. It also includes a laboratory test of remote vibration monitoring in the 3D at Depth 8 meter test tank. This task includes six subtasks.

6.4.1 Identifying an open-water trial of opportunity and developing the concept of operations

3D at Depth was given the opportunity to team with Monterey Bay Aquarium Research Institute (MBARI) to perform sea bed mapping from their ROV platform in open water. Two such missions were available and performed, one in December of 2013, and again in May of 2014.

MBARI has an ongoing research program to perform ocean floor imaging using multibeam sonar and color photography (http://www.mbari.org/data/mbsystem/). The plan was to integrate the SL1 sensor with the MBARI "Doc Ricketts" ROV and then collect sea bed data over several days. The ROV would be piloted over the seabed in a "push broom" fashion to image the sea bed. This was the first time the SL1 laser sensor was used in this manner. Water depths approached 3000 meters. The MBARI "Doc Ricketts" ROV is shown below in the moon bay.

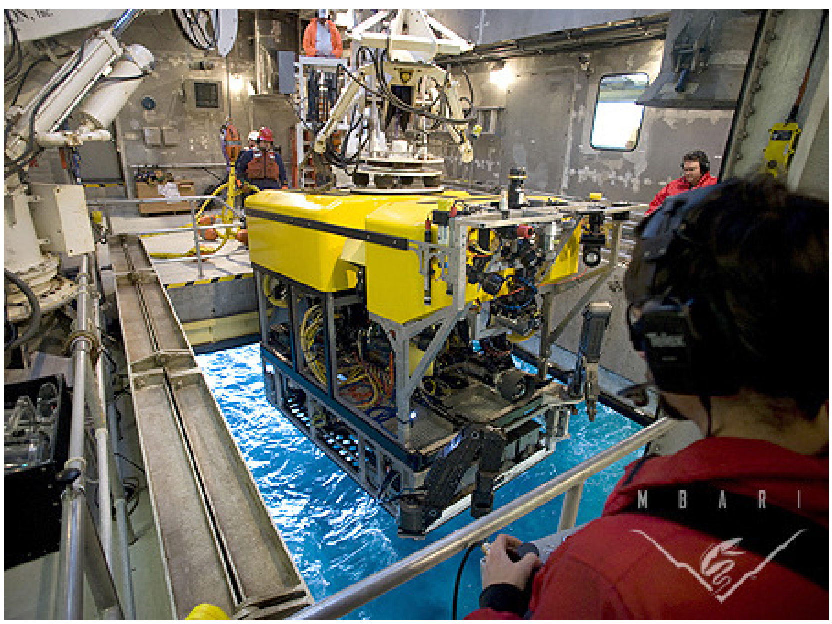


Figure 24: MBARI ROV

Photo curtesy of MBARI (http://www.mbari.org/data/images/ships-facilities/ships-facilities_images.htm)

Both missions were highly successful and met all objectives for data collection and processing, as is discussed in Section 6.4.3.

6.4.2 Updating the system from lessons-learned

Based on the results and lessons learned from previous lab, pool, and open water tests, 3D at Depth implemented several additional upgrades to the system prior to the open water trials.

- An Optical Control Board (OCB) subassembly was created to enhance eye safe modes and manage all signals pertinent to the optical assembly. Such consolidation of control increases safety and reduces the monitoring load of the main processor. A microprocessor was placed on the OCB with primary duties to communicate with the laser and provide millisecond monitoring of the eye safety mechanism. In addition, the OCB paved the way for ease of development for the SL2 which has the optical assembly in a separate housing from the main processor. Adding processing control to the optical assembly of the SL2 sensor also greatly decreased the number of discrete signals communicated between the two enclosures.
- Upgrades were made to the mounting plates and hardware of the both SL1 and SL2. Many important lessons were learned during offshore handling of the instruments and mounting to various ROV platforms. Enhancements were made for both ROV deck and rack mount locations.
- Development of a separate Power/Communications Interface (PCI) product which provides a more generic power and communications interface between the SL sensor and the ROV. This additional product proved to provide more reliable power and communications integration with a wider variety of ROVs.
- Integration of a pan unit to enable 360° azimuth scans.
- Integration of a pan/tilt unit to enable 360° azimuth scans and 130° elevation scans.
- Developed a safety warning light that improves safety while performing deck tests or diver operations.
- Developed specialized shipping cases to ease packing burden and to protect the sensor and assemblies during shipment and while on standby shipboard.
- Further enhancements to the software that controls the sensor, processes the data, and visualizes the resulting point cloud

6.4.3 Performing the open water trials and data processing for 3D imaging system from a moving platform

This section covers the integration and results of the moving platform open water tests.

6.4.3.1 SL1 ROV mechanical integration

The SL1 was mounted on the lower "cage" of the ROV and pointed downward, with a side to side scanning orientation, as shown below. Precise measurements were taken between the SL1 sensor and the Navigation system, slightly behind the sensor. The SL1 received power from a custom power bottle on the ROV which supplied the required 24 V DC. The SL1 sensor was also wired through the ROV interface providing Ethernet control of the sensor shipboard.

Figure 25: Mechanical SL1 Integration on MBARI ROV.

6.4.3.2 SL1 Software Integration

Sensor software was written to provide a serial connection via an auxiliary port to the ROV navigation system. This software connects to the navigation system and records current attitude and position with a timestamp.

The laser data and navigation data sets were provided to MBARI and processed using their MB-System software. MB-System is an industry standard post processing tool for processing and display of bathymetry and backscatter imagery data derived from multibeam, interferometry, and sidescan sonars. It was upgraded to allow input and processing of laser data. The MB-System software is open source and widely used in research environments.

6.4.3.3 SL1 Sea Bed Mapping Results

An output image from the MB-System utilizing laser data is shown below. Depth above sea bed is depicted with color shading. The vertical lines depict ROV path as it traversed the push broom pattern. The “speckle” is an actual clam bed at close to 3000m depth. The entire image represents approximately 30m x 30m area.

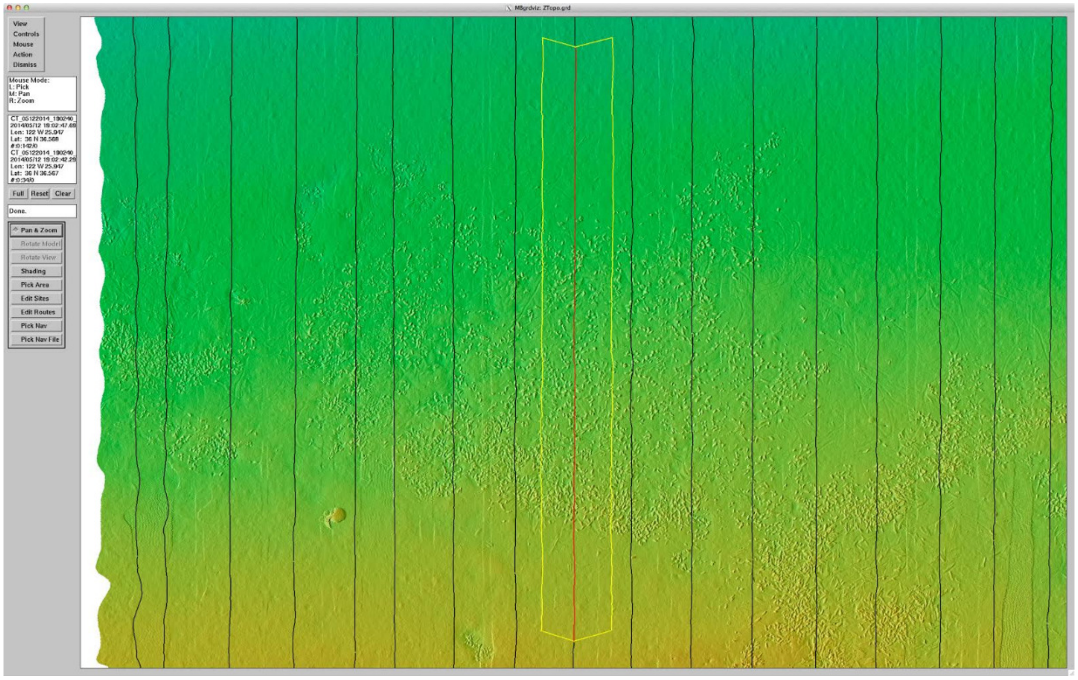


Figure 26: Motion Corrected Scans of Seabed using MB-System. Distance between black lines is approximately 2 meters.

Additional software was also written in the 3D at Depth Processing Tool to utilize the time based navigation data alongside the laser data to compute a 3D point cloud of the sea bed and clam field. The laser data was corrected using navigation position and attitude. The laser data point cloud below is nearly 3.4 million data points taken over a 50 minute period. Figure 27 represents approximately 20m x 45m area.

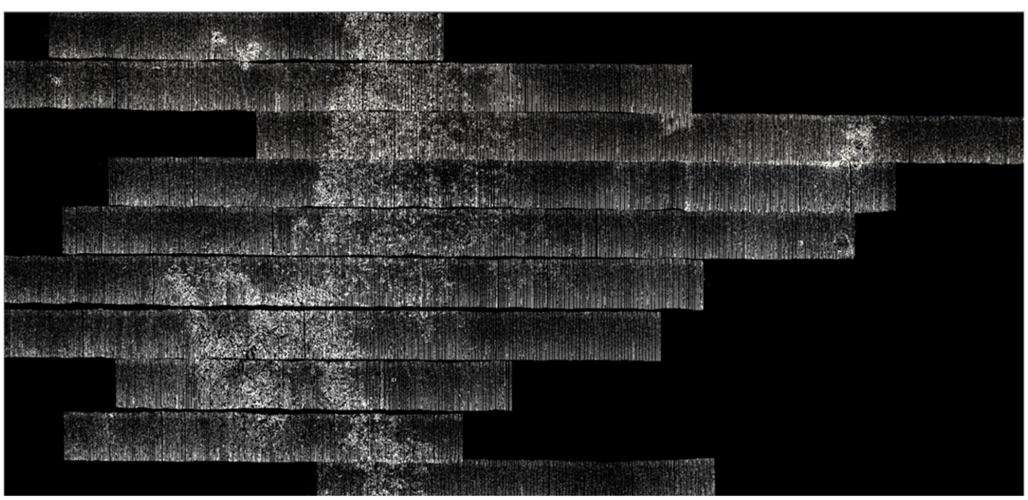


Figure 27: 3D Point Cloud of a clam bed. Swath distance is approximately 2 meters.

Figure 28 is a more isometric view of the 3D point cloud. In this view the 1-2cm clam bed height can be seen above the sea floor.

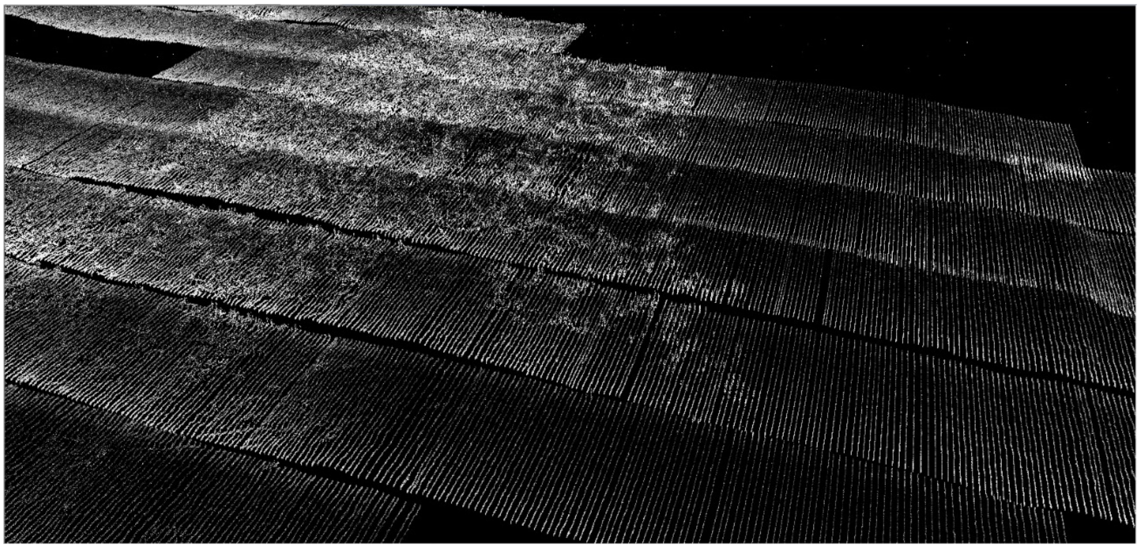


Figure 28: 3D view of the clam bed scans

6.4.3.4 Analysis

This task validated the capability to motion correct scanned datasets using industry standard and custom post processing tools. Although the data was collected in late 2013, using the enhanced post processing tools, the data was corrected months later using the INS data stream and laser scans. This demonstrates the ability to correct datasets as a post collection task and provides the capability to accurately map sea beds, fields, and pipeline corridors.

The next step for developing the technology will be calibrated open water tests where known targets are scanned from a moving ROV in open water and the point cloud measurements compared to the truth measurements.

6.4.4 Performing the open water trials and data processing for survey metrology from a stationary platform

The first demonstration of using the SL1 in a production environment occurred in January 2014. During a metrology campaign in the Gulf of Mexico, Technip provided the opportunity to perform jumper metrologies using the SL1 and traditional acoustic LBL. The campaign included performing 13 metrologies over a six week period in which the two methods were to be completed for the first four measurements and if the subsea LiDAR system proved to have similar accuracy, then the remaining metrologies would be performed using the SL1 as the primary tool.

CDL as a cost share partner provided a power and communications interface bottle for ROV integration. Technip provided project access, vessel time and accommodation for the 3D at Depth engineer.

The SL1 was mounted on the crash cage of the XLX ROV. The mounting location allowed for a line of sight where trees, manifolds and PLETs could be scanned from a single location. In some cases, due to the project schedule, a tooling skid was attached to the bottom of the ROV, providing more height and improving the line of sight.

Figure 29: SL1 Mounted on an XLX ROV

The maximum distance between structures for the metrology was 90 feet which required that the SL1 be positioned between the structures. For redundancy, the sensor collected data from two reciprocal positions for each metrology as depicted in the following AutoCAD image.

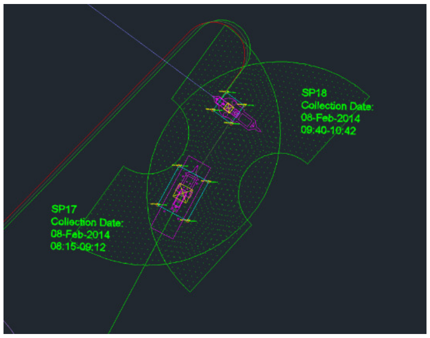


Figure 30: AutoCAD Scanning Plan

During the first four metrologies, the LBL acoustic method was used leveraging a hub overshot tool for placing the COMPATTS. Once the LBL methods were completed, the SL1 was deployed to scan the same structures.

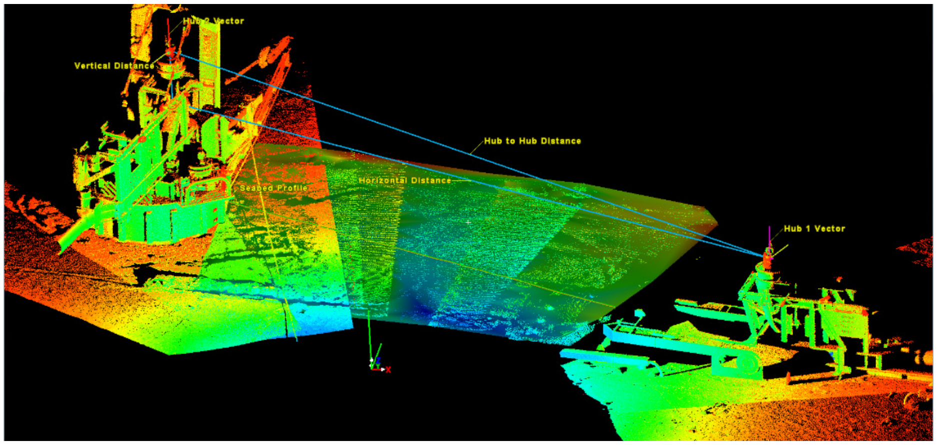


Figure 31: Laser Metrology Point Cloud and Vectors

Once the point clouds were collected, they were imported into Cyclone where the hubs were derived using best fit cylinders. Although there were up to 9 individual scans, they shared the same coordinate system since each scan was simply rotated about the Z axis using the pan motor. The exact angle of the rotation is known from the pan unit encoder. Therefore when importing the scans, they were automatically linked through the pan angle, thus creating a single point cloud for the entire scan position.

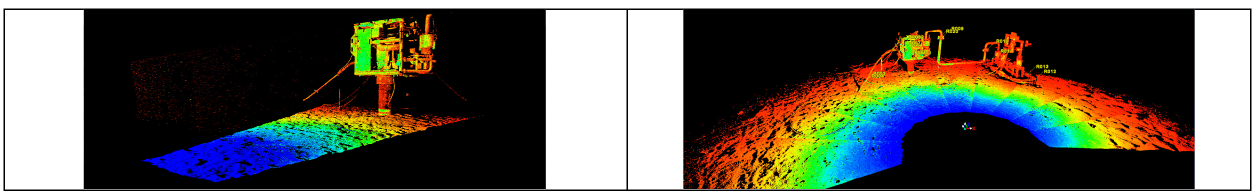


Figure 32: (Left) Single 30° x 30° scan (Right) Nine scans linked to the same coordinate system with different pan angle values

Cylinder centerlines were then created and formed the hub vectors. Using dimensional control data from the structures which were collected topside at the fabrication yard, the hub centers were located from the point cloud therefore providing the 3D vectors for the two hub vectors. In addition to the hub vectors, a seabed profile was derived by creating a surface model from the point clouds and intersecting the surface with the place between the two hubs.

The hub vectors and seabed profile were imported into AutoCAD, dimensioned, and then formatted into a jumper fabrication drawing. The key measurements derived from the process included:

- Horizontal distance between the hubs - L
- Vertical distance between the hubs - H
- Roll angles of each hub – B and D
- Pitch angles of each hub – A and C
- Distance between the lower hub and the seabed at specific locations

When compared, the average deviations for the six measurements were within tolerance for Technip which prompted the project team to use subsea LiDAR for the remaining metrologies.

The jumpers fabricated from the SL1 metrologies were installed in March 2014 without issues proving the utility of the system for subsea jumper metrology applications.

6.4.5 Two Housing Sensor and Open Water Trial

Lessons learned from mounting on ROVs, along with larger FoV requirements, pushed a design where the sensor could be mounted on a pan/tilt unit. The result was development of a two-housing sensor with a pan/tilt capability to increase utility of the product for scanning as-builds and performing metrologies. The task concluded with a field test of the sensor in an open water scenario where the sensor was mounted on a ROV with a pan/tilt stage.

6.4.5.1 Turbid water tank trial – SL2

A tank trial was conducted October 13-17th 2014 in Aberdeen, Scotland to test the capability of the 3D at Depth SL2 laser scanner to collect as-built datasets in turbid water environments. The expanded field of view of the SL2 combined with the smaller footprint suggests that the system can collect data in more turbid water conditions and in small enclosures.

The first test consisted of 3D scans taken with the SL2 sensor while mounted on a tripod. Despite the murky water conditions the SL2 was able to collect high resolution intensity and 3D data of the test structure. Due to the murkiness of the water the SL2 range was limited to approximately 3 meters.

Figure 33: Test tank and target structure prior to flooding

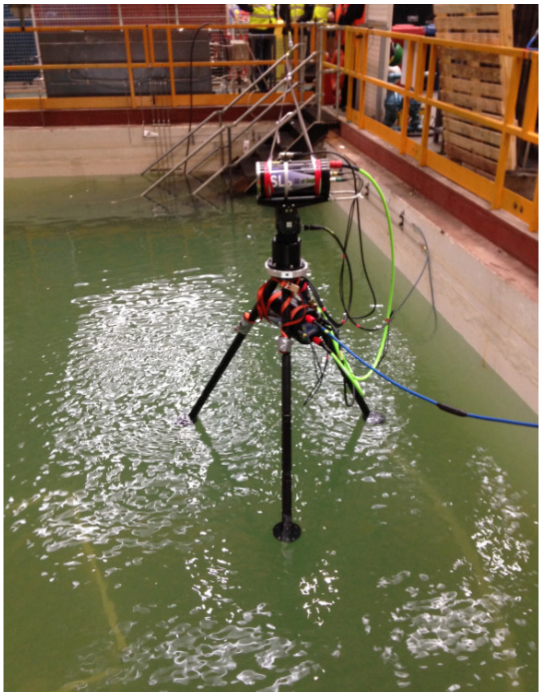


Figure 34: SL2 being lowered into the test tank of highly turbid water

Figure 35 shows a 2D intensity image of a single high resolution scan. The image is detailed enough that the ribs in the support webbing can be seen, along with a weld. The bolts are also clearly visible. Imaging of this clarity could be useful for general inspection of flanges and pipes, even in these turbid water conditions.

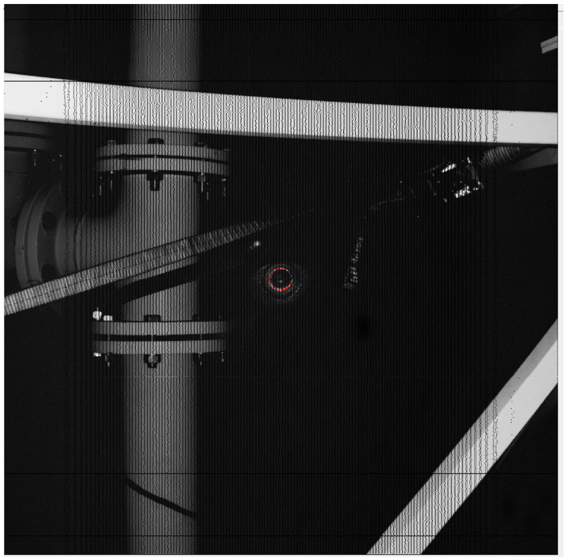


Figure 35: Short range scan - greyscale intensity map

Figure 36 below is the same dataset but shows the 3D point cloud of the data. While the "image quality" is not as nice as the previous Figure, this is the real X,Y,Z data so measurements can be made from the 3D point cloud. In this screen shot color is mapped to intensity. It is this 3D point cloud that can be registered with other point clouds from other scan positions to build up a model of the structure. This point cloud model can then be imported into a CAD package to produce a full "current state" CAD model of the structure.

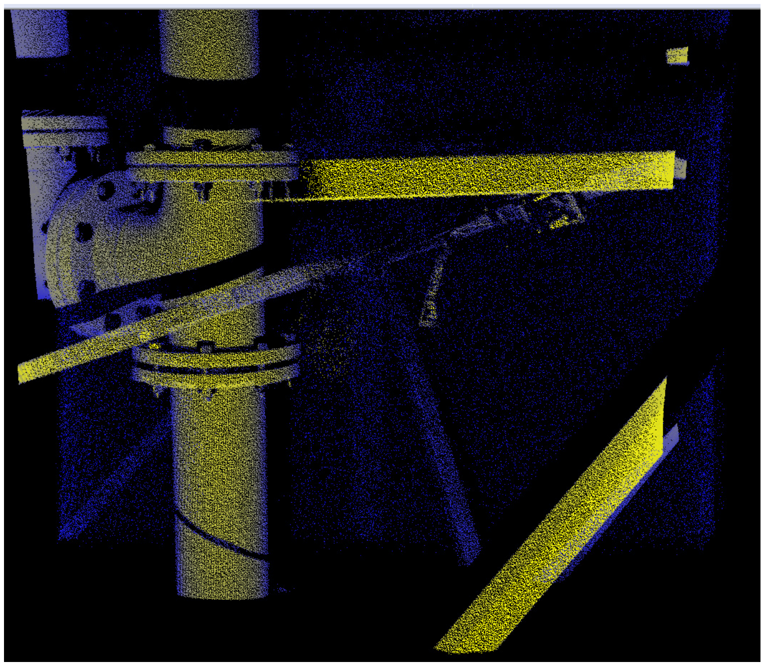


Figure 36: Tripod based 3D point cloud. Same dataset as the previous image. Color is mapped to intensity.

This tank test was the first water test of the two-housing system mounted on a pan-tilt stage. It was also a good test of the base technology in turbid water conditions. The test validated that the sensor can operate in turbid waters, but with a greatly reduced range (~3m max range as opposed to over 30m in clear open water). When operating at close range a pan/tilt capability is needed in order to combine the multiple small area scans of the up-close structure.

6.4.5.2 Gulf of Mexico Open Water Trial – SL2

Technip US sponsored a project in November 2014 to perform a spool piece as-built using the SL2 laser scanner. The system was mobilized on a FMC/Schilling HD ROV and tasked with scanning existing spool pieces and their supporting brackets in order to fabricate replacement components.

Figure 37: SL2 System Mounted on an HD ROV

The operation was in relatively shallow water depths of 200 feet. The spool pieces were part of the export risers for a TLP and had complex pipe bends which were not represented on the 20 year old design drawings. Since the spools were on a pontoon, there was no place to land the ROV for a stable survey scan. Therefore the team used the fast scan mode which produces a lower resolution point cloud but can collect within one second. Multiple fast scans were collected and registered using Leica's Cyclone software.

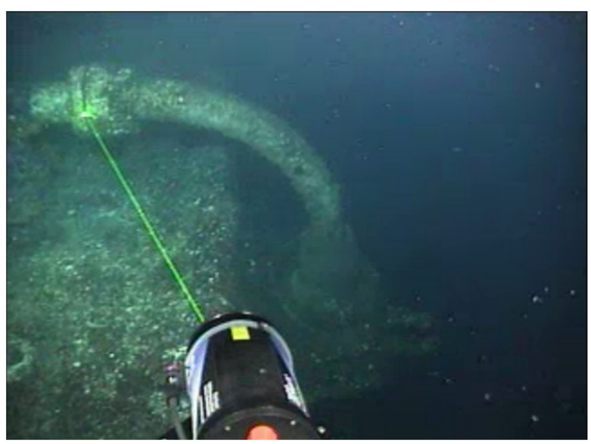


Figure 38: Video image from the ROV camera of the SL2 scanning a spool piece

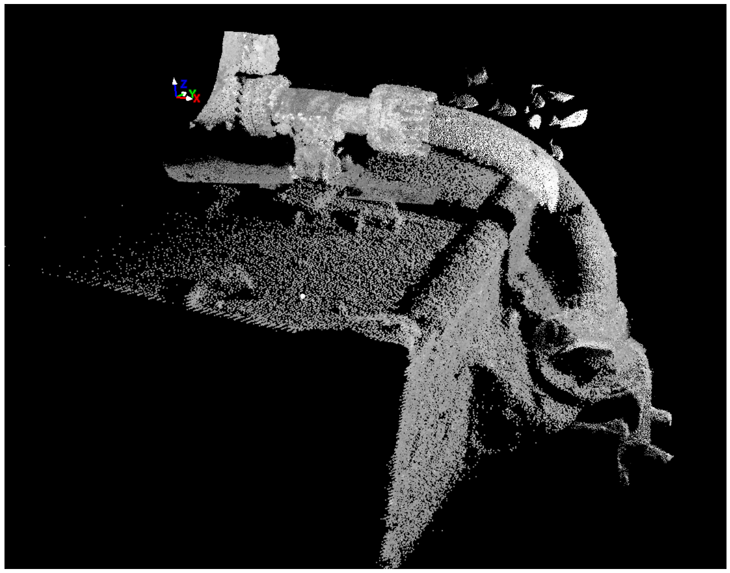


Figure 39: Resulting point cloud of the spool piece constructed from multiple scans at different pan and tilt angles.

The project validated the SL2's ability to both pan and tilt in order to collect specific areas of interest. The fast scan mode allowed the team to overcome the instability of the ROV while hovering in place and produced an accurate point cloud which was ultimately used to develop the resulting CAD model for the spool piece as-built.

6.4.6 Vibration Measurement Tests

The goal of this task was to develop and test a new capability for vibration measurements. In some applications, operators are interested in the vibration of their assets particularly when considering risers, jumpers and other critical structures. Under this task new algorithms and sensor software was developed and verified to enable vibration sensing. This task also included developing a calibrated lab test device to compare known motion distance and frequency while testing in the 3D at Depth 30 foot tank in the lab. The task concluded with a calibrated lab test and verification of vibration rates.

Figure 40 shows the calibrated test device mounted on the end of the 30 foot long test tank. The target is a square piece of aluminum mounted on an arm to lower it into the tank water.

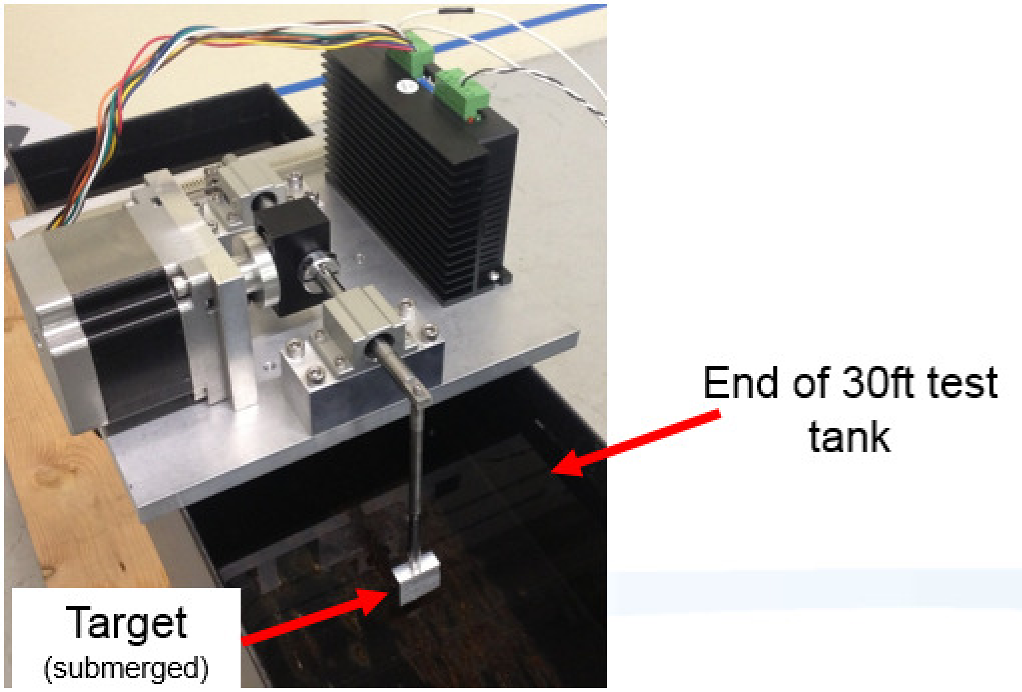


Figure 40: Calibrated test fixture attached to the end of the 3D at Depth 30 ft. test tank

Figure 41 shows the custom test device in more detail. The eccentric is designed to provide 3cm of stroke distance (+/-1.5cm). The Revolutions per Minute (RPM) of the stepper motor are measured with a Veeder-Root 6611 hand tachometer. The frequency of the target motion is then calculated based upon the RPM measurement.

The oscillating frequency is calculated from RPM based upon 1Hz = 60 RPM.
Therefore, 600 RPM / 60 = 10Hz.

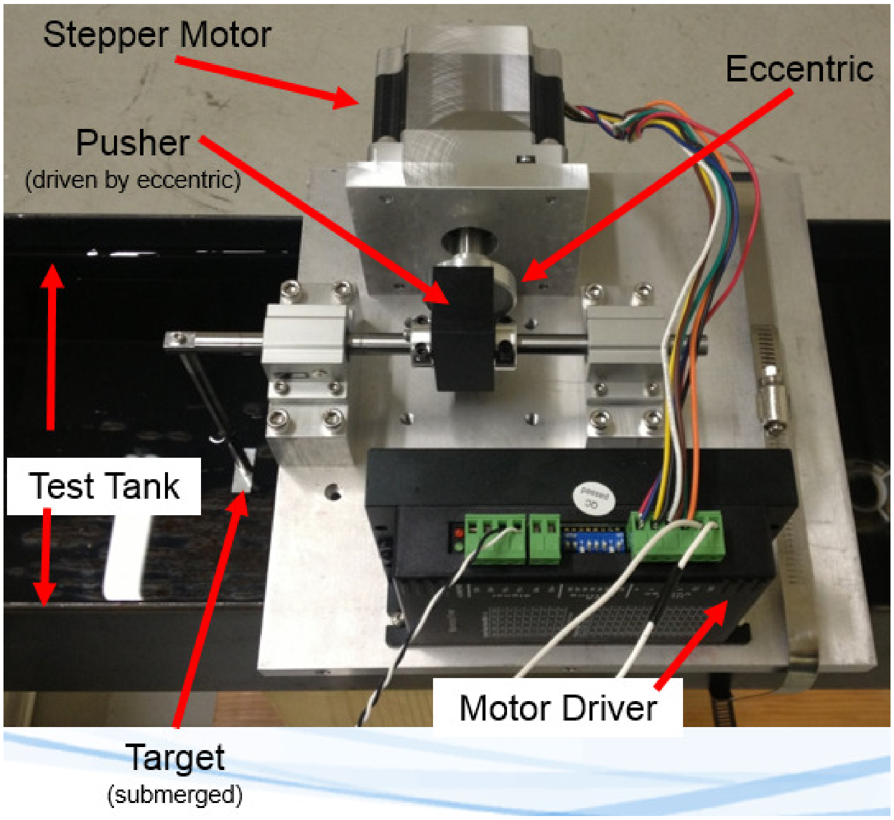


Figure 41: Details of the custom vibration test fixture that provides known, calibrated motion distance and frequency

The test fixture was designed, built, and attached to the test tank. The SL2 laser scanner was placed at the other end of the test tank approximately 8.8 meters away. The laser was steered to hit the target directly. The test system was then calibrated to run at 2Hz while the laser collected data. Figure 42 below shows the data captured by the laser scanner.

The x-axis is time in seconds, while the y-axis is range in meters measured by the SL2 sensor. A close examination of the y-axis shows a range displacement measurement of approximately 3.1cm. This is very close to the designed 3.0cm, thus verifying the ability of the laser sensor to measure the vibration displacement.

For frequency, it is easy to count approximately 2 cycles in 1 second, or 2Hz. Figure 43 shows the frequency spectrum with a peak at 1.88Hz.

This first test therefore shows the ability of the laser sensor to measure both frequency and range displacement of a vibrating target at greater than 8m range for a low frequency of 2Hz.

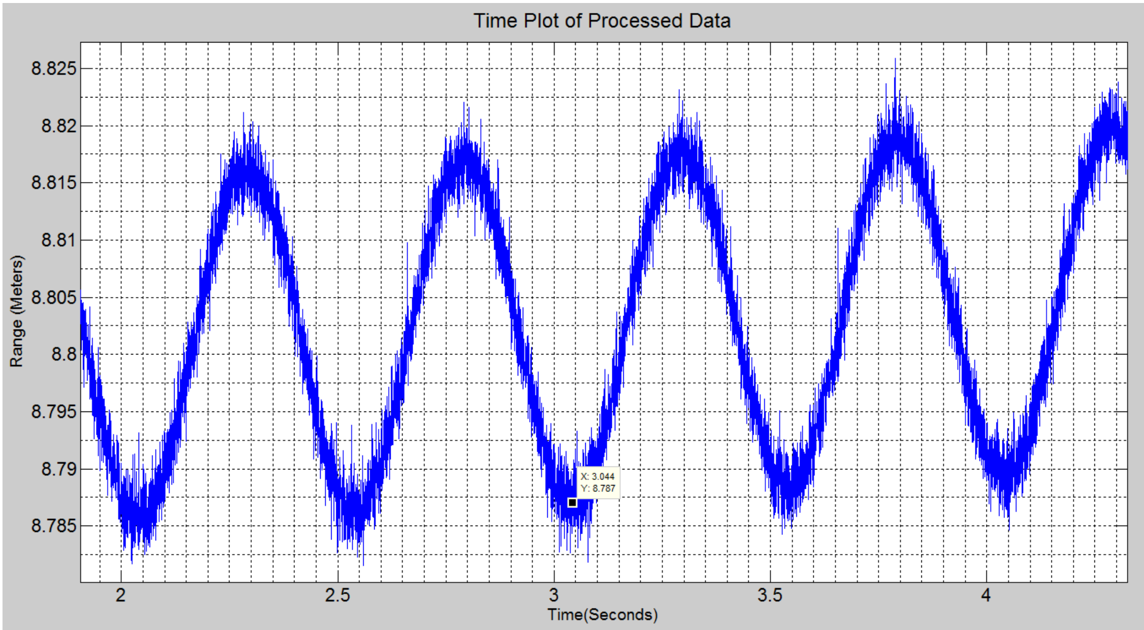


Figure 42: Time plot of signal return for 2Hz test. 8.8m standoff range in the test tank

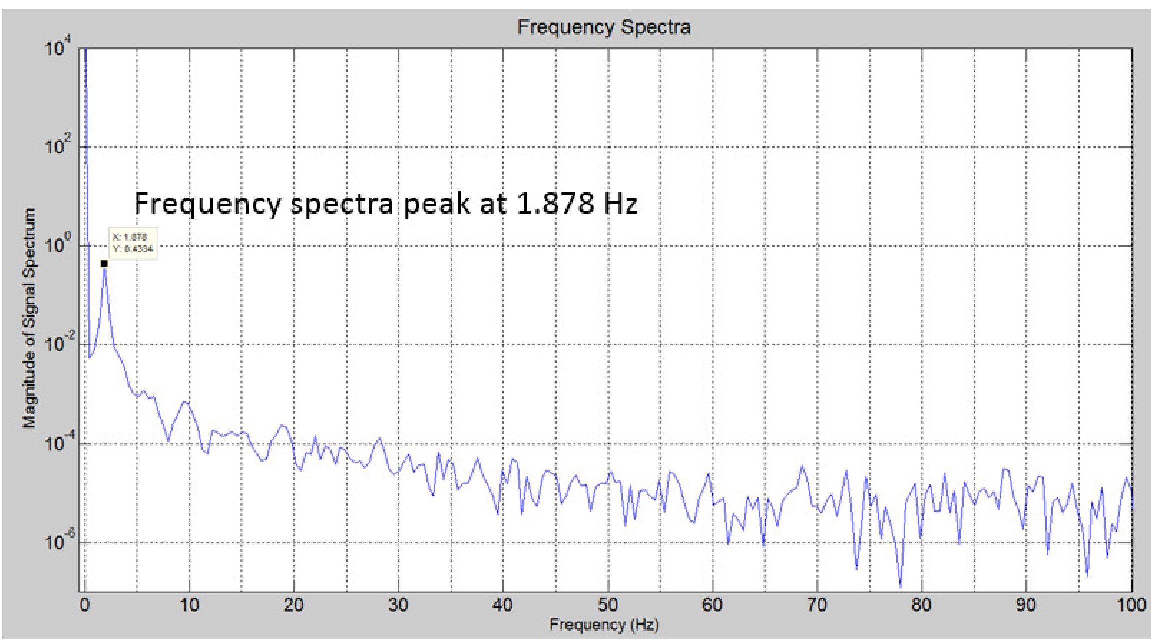


Figure 43: Spectral plot of signal return for 2Hz test. 8.8m standoff range in test tank

For the next test the frequency was increased to 10Hz. Figure 44 shows the time plot of data recorded by the sensor, revealing a measured displacement of approximately 3.0cm. A close examination of the y-axis shows that a range displacement down to +/-5mm is easily achievable.

For frequency, it is easy to count approximately 10 cycles in 1 second, or 10Hz. Figure 45 shows the frequency spectrum with a peak at 9.86Hz.

This test therefore shows the ability of the laser sensor to measure both frequency and range displacement of a vibrating target at greater than 8m range for a frequency of 10Hz.

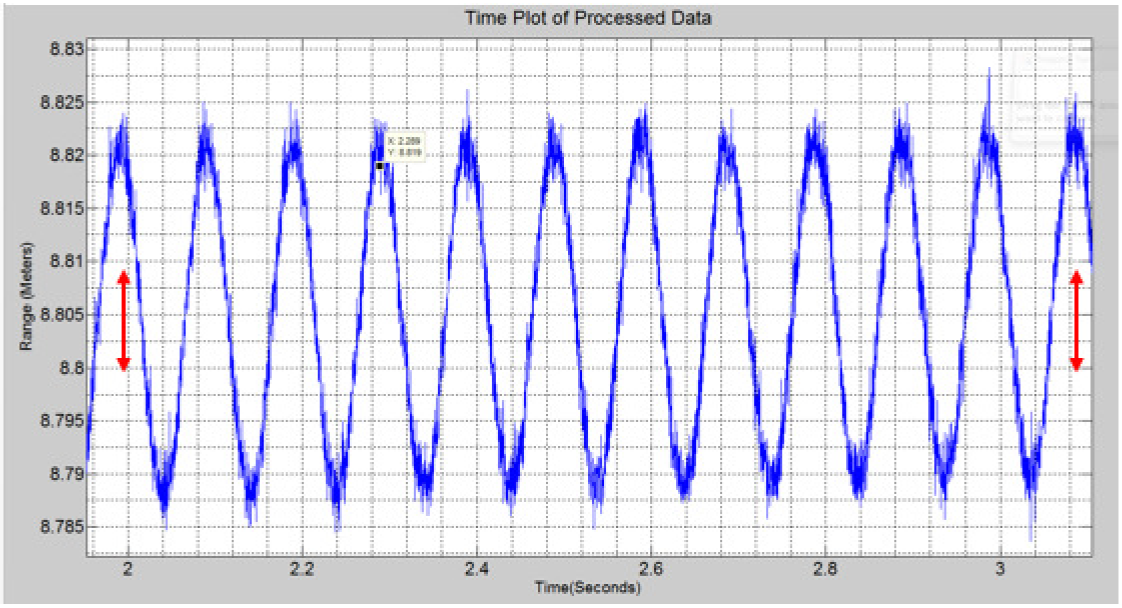


Figure 44: Time plot of signal return for 10Hz test. 8.8m standoff range in the test tank

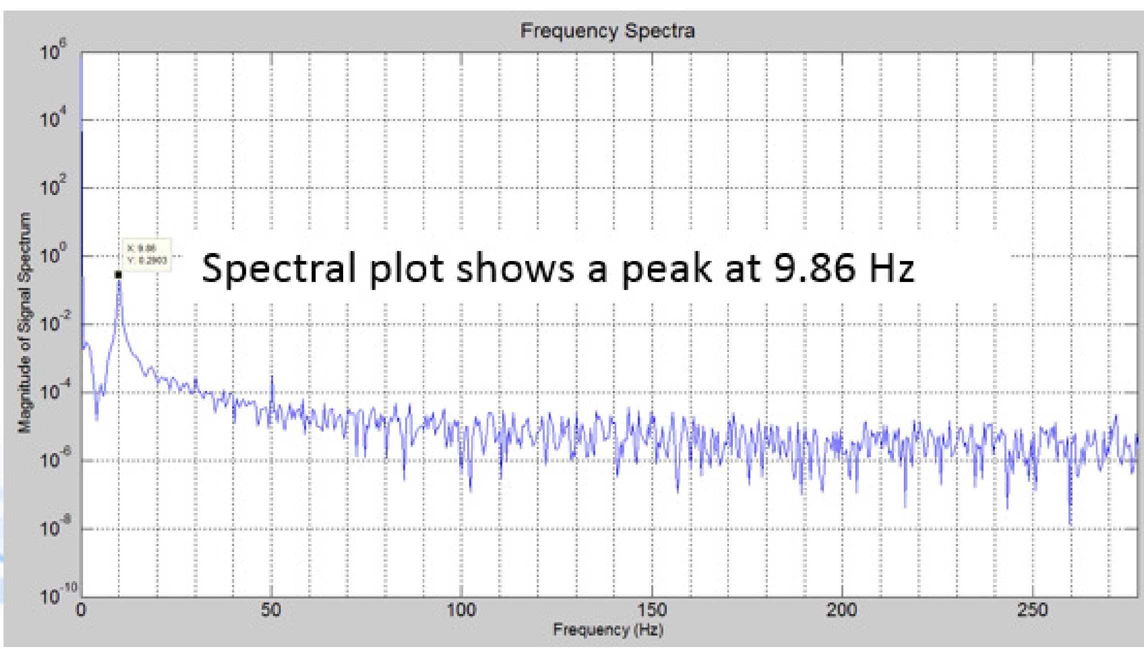


Figure 45: Spectral plot of signal return for 10Hz test. 8.8m standoff range in test tank

For the next test the frequency was increased to 15Hz. Figure 46 shows the time plot of data recorded by the sensor, revealing a measured displacement of approximately 3.4cm. The increase in measured displacement is believed to be due to induced wobble in the target rod because at this speed the entire test system was vibrating. The entire system vibrated to the extent that the frequency was not increased further for safety concerns.

For frequency, it is easy to count approximately 15 cycles in 1 second, or 15Hz. Figure 47 shows the frequency spectrum with a peak at 15.02Hz.

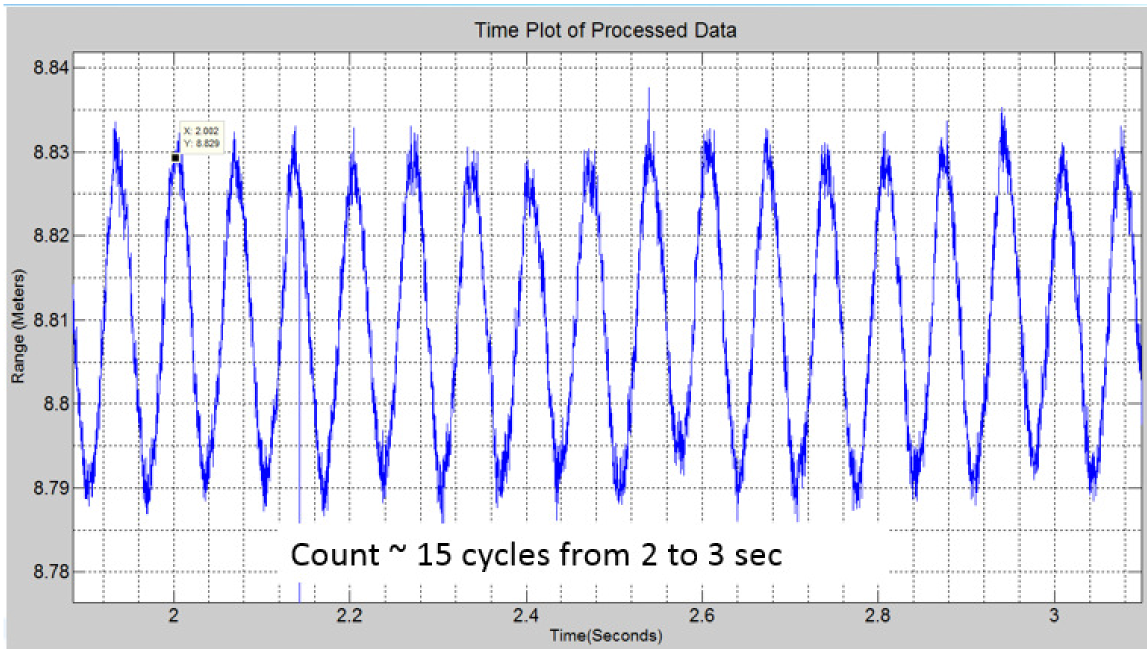


Figure 46: Time plot of signal return for 15Hz test. 8.8m standoff range in the test tank

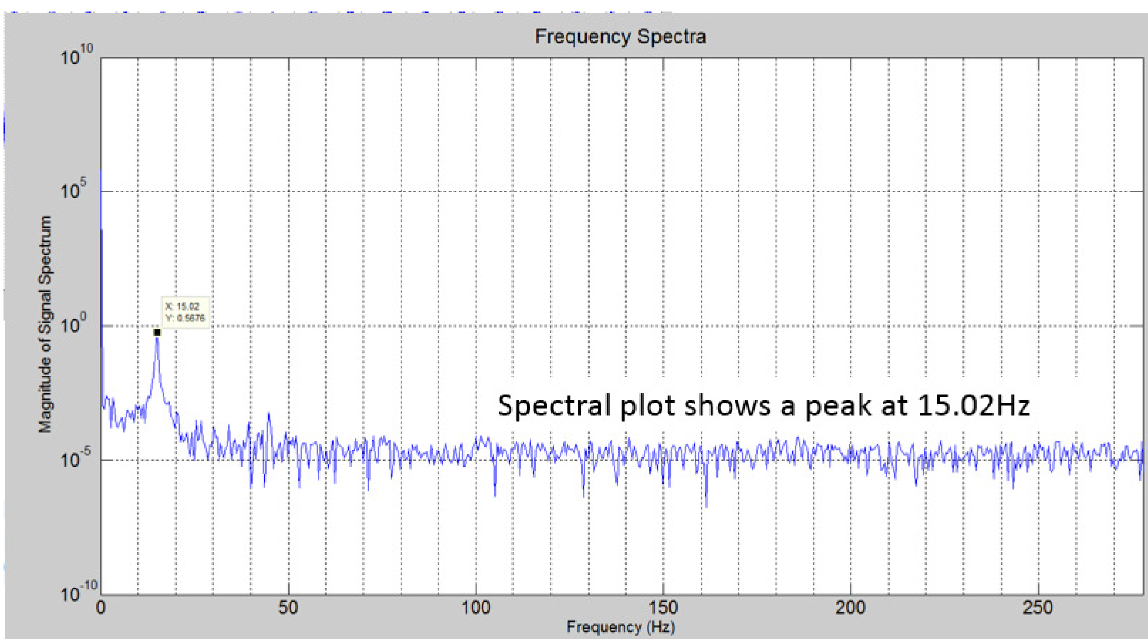


Figure 47: Spectral plot of signal return for 15Hz test. 8.8m standoff range in test tank

This series of tests quantitatively showed the ability of the laser sensor to measure both frequency and range displacement of a vibrating target at greater than 8m range underwater. A range displacement sensitivity of better than +/-5mm was demonstrated for a frequency range of 2Hz to 15Hz.

7 IMPACT TO PRODUCERS

There were a number of benefits realized from Technip's first laser metrology project, both financial and operational, with a time saving of 104 hours of vessel savings for the 13 metrologies. At approximately $120,000 per day for the vessel, the cost savings for this one project totaled over $500,000. And this did not account for the added costs of metrology tooling, crane operations, and other components which could not be quantified on this one project.

For the producers, this savings translates directly to the ability to achieve first oil in a reduced timeframe.

As well as fulfilling its promise as a metrology tool, it became apparent during the development that the *SL1* could be used for alternative applications, such as scanning in-situ subsea structures in established 'brownfield' sites, where no as-built data may exist. The SL1 was subsequently used for this very purpose in mid-2014, where it was deployed to assess the condition of an aging drill center. In a few days, a full 3D model of the drill center was presented to a team tasked with updating the infrastructure and the models provided a valuable tool for planning and remediation (See Figure 48 below).

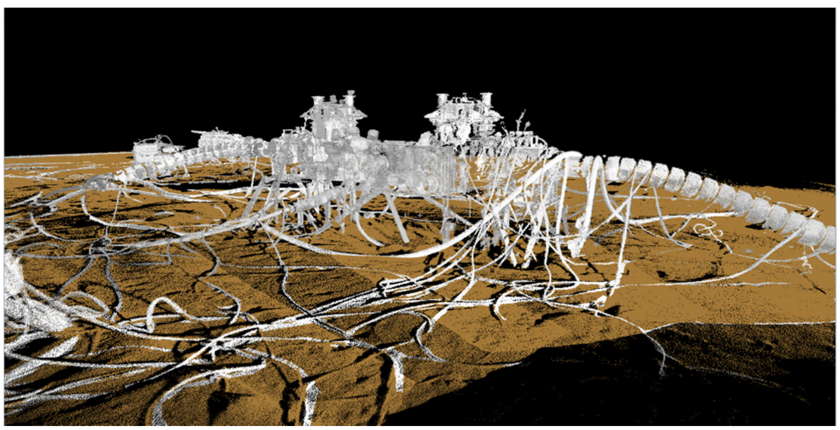


Figure 48: Drill center as-built model collected with the SL1

Point cloud data has become ubiquitous in today's engineering environments. Popular software CAD packages such as AutoCAD and SolidWorks as well as GIS tools can import native point cloud formats. This allows users to leverage these datasets for a variety of applications within their familiar desktop applications.

Close range scanning during ROV inspection operations will allow assessment of conditions such as Anode depletion, weight-coat damage to pipelines, and insulation damage to jumpers. Hazards can be quickly identified and mitigated. It is obvious that the *SL1* will be a critical tool for IMR (Inspection, Maintenance, and Repair) campaigns to enable and validate more environmentally safe operations.

The main benefit in terms of metrology is a marked improvement in operational efficiency, leading to significantly less time spent on each metrology. As previously stated, conventional methods can take between 12 and 18 hours per metrology, including 10 hours 'on-bottom' measurement time. Once the *SL1* was up and running, the average time spent 'on-bottom' gathering data for each metrology was only

2 hours. If a structure had already been dimensionally scanned on the surface prior to deployment, then this process would have been even faster, allowing a quicker alignment of the subsea point cloud.

Added value was seen in the following aspects:

- No need for specialist LBL transponder brackets or docking receptacles on the manifolds and assets
- High reduction in rigging equipment, i.e., no over boarding and deepwater deployment of transponders necessary
- No surface crane operations required. (On longer spools, tripod with spherical registration targets would be deployed to register scans.)
- **No touch required of the subsea assets as is required with the standard LBL method.** It was not necessary to place laser targets on the structures, as common distinct points such as corners, straight edges, etc. could be used to register scans.

Improvements to the overall subsea scanning process can be greatly approved with the addition of survey targets to structures that can be easily located using point cloud processing tools. By attaching survey targets to the structures and then scanning the structures prior to deployment, the subsea scanning process could be optimized by focusing on collecting a small set of defined features and then registering the top side scan into the subsea point cloud. As subsea scanning becomes more widely accepted, the operators can begin to alter their topside engineering and survey practices to align with this new subsea capability.

8 TECHNOLOGY TRANSFER EFFORTS

Technology transfer is a key component of the RPSEA project charter, providing educational outreach and program overviews. A majority of the technology transfer activities were presentations given at the various RPSEA conferences and Technical Advisory Committee (TAC) meetings, as well as industry conferences where the private/public partnership were highlighted.

During early 2013, the first subsea trial was completed in the Gulf of Mexico, which moved the project discussions from theoretical lab and controlled environment exercises into real world applications. After the first successful LiDAR metrology project was completed in early 2014, 3D at Depth was invited to present this new capability at the SPAR conference in Colorado Springs. This conference is focused on the business of point cloud data collection and processing and for the first time featured an underwater track. 3D at Depth presented two specific topics; the RPSEA private/public partnership and subsea metrology using LiDAR.

In addition to the various technology transfer activities, 3D at Depth supported two projects in conjunction with the US National Park Service's Submerged Resources Center. These projects, although not traditional technology transfer activities, showcased this new underwater LiDAR capability in a new market – cultural preservation. The projects included surveying the USS Arizona - a cultural icon from WWII, and surveying sunken rowboats in Yellowstone Lake – cultural icons from the 1950's. These projects spawned newspaper articles, television spotlights, and articles in technical journals.

Articles from the USS Arizona Survey project included:

http://www.deskeng.com/virtual_desktop/?p=8788&utm_source=rss&utm_medium=rss&utm_campaign=memories-of-the-uss-arizona-resurface-in-3d

http://autodesk.blogs.com/between_the_lines/2014/06/uss-arizona-in-3d-project-behind-the-scenes.html

https://www.youtube.com/watch?v=qRO5f-bnNhs&feature=youtube_gdata

Blog from the Yellowstone Scanning Project:
http://www.owuscholarship.org/blog/?p=3304

These projects demonstrated the ability for RPSEA programs to support capabilities outside of the traditional oil and gas industry and highlighted the success of the private/public partnership and its effect on the cultural preservation of key US landmarks which are difficult to accurately document.

Technology Transfer Activities

Date	Event	Location	Topic	Presenters
4/30/2011	Offshore Technology Conference (OTC)	Houston, TX	RPSEA Project	Carl Embry Mark Hardy
5/31/2011	RPSEA Subsea Systems TAC Meeting	Houston, TX	RPSEA Project	Carl Embry
7/25/2011	RPSEA UDW Technology Conference	Houston, TX	RPSEA Project Overview	Carl Embry Mark Hardy
9/13/2011	RPSEA Subsea Systems TAC Meeting	Houston, TX	RPSEA Project Update	Carl Embry
1/28/2012	RPSEA Subsea Systems TAC Meeting	Houston, TX	RPSEA Project Update	Carl Embry
5/1/2012	RPSEA Subsea Systems TAC Meeting	Sugarland, TX	RPSEA Project Update	Carl Embry
5/1/2012	Offshore Technology Conference (OTC)	Houston, TX	RPSEA Project Progress	Carl Embry Mark Hardy
9/19/2012	RPSEA UDW Technology Conference	Houston, TX	RPSEA Project Progress	Carl Embry Mark Hardy
4/14/2013	Subsea Tieback Conference	San Antonio, TX	Booth with CDL – demonstrating subsea LiDAR	Mark Hardy
5/9/2013	Offshore Technology Conference (OTC)	Houston, TX	RPSEA Project – Offshore Results!	Carl Embry Mark Hardy
5/27/2013	RPSEA Subsea Systems TAC Meeting	Sugarland, TX	RPSEA Project Update	Carl Embry
10/29/2013	RPSEA UDW Technology Conference	Houston, TX	RPSEA Project Update	Carl Embry
1/27/2014	RPSEA Subsea Systems TAC Meeting	Houston, TX	RPSEA Project Update – First Offshore Project!	Brett Nickerson
3/10/2014	Oceanology International 2014	London, UK	Subsea LiDAR Metrology	Carl Embry Neil Manning – CDL
4/15/014	SPAR International Conference	Colorado Springs, CO	Subsea LiDAR Metrology	Mark Hardy
4/23/2014	USS Arizona Survey	Honolulu, HI	Survey of the Iconic Battleship	Mark Hardy Carl Embry Brett Nickerson
6/18/2014	Aberdeen Metrology SUT Meeting	Aberdeen, Scotland	Subsea LiDAR Metrology Best Practices	Mark Hardy
6/26/2014	Yellowstone Survey	Yellowstone Park, WY	Survey of cultural rowboats	Mark Hardy
6/5/2014	RPSEA Subsea Systems TAC	Sugarland, TX	RPSEA Project	Carl Embry

Date	Event	Location	Topic	Presenters
	Meeting		Update	
9/3/2014	RPSEA UDW Technology Conference	Houston, TX	Final Report	Mark Hardy

9 CONCLUSIONS

Three dimensional laser scanning offers a new capability to the industry for quickly capturing survey quality data for construction, repair, and maintenance. This ability to quickly capture high resolution 3D models provides a key component of integrity management for a variety of production assets. In this project RPSEA and 3D at Depth further developed the technology and work flows for an underwater 3D laser scanning sensor.

The goals for this technology development program were all met and are still in-line with industry requirements. A list of achievements includes:

- Validated the operational capability of the sensor for deepwater data collection aboard ROVs in non-ideal water clarity conditions.
- Successful operation at depths up to 2990meters.
- Successful operation in conditions where ROV camera visibility was less than 2meters.
- Acquired point clouds of subsea assets and effectively generated 3D models of the assets.
- Integrated with over five different work class ROVs and several tripod based deployments.
- Accuracy proven to less than 1 cm of in-air measurements at ranges up to 45meters.
- Validated Survey metrology results in open water when compared to traditional acoustic methods. All jumpers were installed successfully.
- Acquired laser and navigation data from a moving ROV at 2990meter depth and post-processed the data to produce a 3D point cloud from 50 minutes of collected moving data.
- Developed a two-housing sensor which allows mounting on a pan/tilt unit to enable 360° Azimuth x 130° Elevation scans and performed a successful open water trial.
- Performed a series of tests that quantitatively showed the ability of the laser sensor to measure both frequency and range displacement of a vibrating target at greater than 8m range underwater. A range displacement sensitivity of better than +/-5mm was demonstrated for a frequency range of 2Hz to 15Hz.

The almost 4 year combined Phase 1 / Phase 2 program met all cost share goals, surpassed technology transfer requirements, and RPSEA costs were slightly under budget. In addition, a new technology platform was commercially introduced to the industry that enables better integrity management of assets by providing survey quality 3D data of underwater assets.

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12 GLOSSARY

- AutoCAD – an industry leading 2D and 3D design, drafting, modeling and engineering software tool developed and marketed by Autodesk. The metrology drawings were produced in AutoCAD
- AUV – Autonomous Underwater Vehicle
- Cyclone – an industry leading point cloud processing and modeling tool used to create CAD models from 3D point clouds; developed and marketed by Leica Geosystems. The point clouds were processes using Cyclone.
- DC – Dimensional Control
- FoV - Field of View
- GoM – Gulf of Mexico
- IMR – Inspection, Maintenance, and Repair
- Laser Scanning – a LiDAR application where a laser pulse is moved in two axes over an area of interest effectively painting surfaces and extracting a 3D model of the objects
- LBL – Long BaseLine
- LiDAR – Light detection and ranging; technology where a pulse of light is used to measure distances also known as LADAR
- MBARI - Monterey Bay Aquarium Research Institute
- PLET – Pipeline end terminator
- Point clouds - laser scanning produces a point cloud which is set of X,Y,Z points which can then be processed into 3D CAD models
- Registration – the process of stitching multiple scans together to form a cohesive point cloud with one coordinate system (i.e. along a spool piece)
- Registration spheres – high tolerance machined spheres, mounted on a tripod and used to register overlapping scans. The centroid of the spheres can be used to identify a single point. More control points in overlapping scans leads to a higher precision model.
- ROV – Remote Operated Vehicle
- SL1 – the trade name for the 3D at Depth commercial underwater laser scanner
- SPM – Spool Piece Metrology
- Total Station - an electronic theodolite integrated with an electronic distance meter (EDM) to read slope distances from the instrument to a particular point; the predominate tool for surveying and the most precise survey tool on the market. UTEC used a Total Station during the Ohmsett accuracy tests as truth measurements.
- UDW – Ultra DeepWater