FINAL REPORT

Optical Monitoring of Subsea Blowout Droplets and Subsea Dispersant Efficacy

Submitted to:

Bureau of Safety and Environmental Enforcement (BSEE)
Oil Spill Response Research Branch

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31 October 2018

Acknowledgments

This report is part of a study that was funded by the United States Bureau of Safety and Environmental Enforcement (BSEE), Department of the Interior (DOI), Washington, D.C., under Contract Number E17PC00009.

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September 14, 2018

1602129.000 - 5372

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List of Acronyms and Abbreviations

API	American Petroleum Institute
bmp	Bitmap Image Format
BSEE	United States Bureau of Safety & Environmental Enforcement
CCD	Charge-Coupled Device
cm	Centimeter
CPU	central processing unit
d50	Median Droplet Diameter by Volume
DOI	United States Department of the Interior
DOR	Dispersant to Oil Ratio
DWH	Deepwater Horizon
GB	Gigabyte
GoMRI	Gulf of Mexico Research Initiative
GOR	Gas to Oil Ratio
GUI	Graphical User Interface
HTTP	Hypertext Transfer (or Transport) Protocol
IFT	interfacial tension
L	Liter
LED	light-emitting diode
LISST	Laser In-Situ Scattering and Transmissometry
m	Meters
MB	Megabyte
µm	Micron
mm	Millimeter
min	Minute
OGP	oil-gas percentage
OHMSETT	The National Oil Spill Response Research & Renewable Energy Test Facility, Oil and Hazardous Materials Simulated Environmental Test Tank
png	Portable Network Graphics Format
PySilCam	SilCam python package
ROV	Remotely Operated (Underwater) Vehicle
SilCam	Silhouette Camera
SINTEF	SINTEF Environmental Technology
SSDI	Subsea Dispersant Injection
TRL	Technology Readiness Level
VOC	Volatile Organic Compound
Wi-Fi	Standardized Wireless Local Networking

Disclaimer

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This report has been reviewed by the BSEE and approved for publication. Approval does not signify that the contents necessarily reflect the views and policies of the BSEE, nor does mention of the trade names or commercial products constitute endorsement or recommendation for use.

1 Abstract

The accurate monitoring of subsea oil release droplet sizes and the effects of applying dispersants subsea has substantial consequences for decision-making, impact assessment, and scientific understanding of blowout behavior. It is crucial for monitoring technology to address the range and variety of droplets (both oil and gas) in a release plume expected under real world conditions. Measurements and knowledge of the actual droplet sizes that exist under differing blowout or subsea release scenarios are fundamental to response decision making and understanding potential ecosystem impacts. At present, uncertainties and the related scientific debate about the physics and prediction of subsea blowout oil and gas droplet sizes lead to a lack of confidence surrounding oil fate and effects in the water column and the value of subsea dispersant application. Filling the gap in accurate release plume monitoring during large-scale releases can resolve this uncertainty.

Recent developments in an optical in-situ particle imaging system, named the SilCam, have allowed for successful characterization of droplet size distribution of mixed oil and gas releases from in-plume measurements across a realistic range of droplet sizes (100-12000µm), enabling assessment of dispersant effectiveness in real-time on a large experimental scale. We believe that this technology shows sufficient promise to be considered as standard in subsea blowout monitoring, and in quantifying the effectiveness of subsea dispersant injection if it were to be used.

This report outlines the technical principles of obtaining and analyzing data from the SilCam for use in real-scale subsea blowouts, supported by a dataset obtained from a series of large-scale releases of mixed oil and gas, including dispersant injection.

Prototype improvements, a set of large-scale experimental releases, SilCam training and prototype delivery were all completed at OHMSETT in the period from 9^{th} to 25^{th} April 2018. In all, 25 experimental releases were conducted with varying release conditions (GOR, DOR, Nozzle diameter, Release rate) and utilizing SilCam apparatus for monitoring. A SilCam

operating manual and a draft blowout monitoring plan for using SilCam in the event of a deep water oil spill were also provided.

2 Introduction & Background

There is an unmet need for accurate particle monitoring of subsea oil and gas releases, especially if subsea dispersant application is being considered as a response alternative.

Understanding the oil droplet sizes that exist under differing blowout or subsea release scenarios is fundamental to response decision making and assessing ecosystem impact. It is our understanding that existing, commercially available monitoring devices all have significant limitations (e.g., can't differentiate between gas and oil, or have limits in the range of droplet sizes that can be measured). This makes monitoring of a subsea blowout and subsequent dispersant application with these devices of limited practical use in understanding the nature of the release and impact of the response. Furthermore, an ongoing scientific debate about the oil and gas droplet sizes that occur during a blowout creates uncertainty about the fate and effects of oil in the water column and the value of subsea dispersant application. This was especially evident in the differing academic views expressed at recent Gulf of Mexico Research Initiative (GoMRI) Conferences. Some scientists indicate that the turbulence level in a release like Deepwater Horizon (DWH) creates such small droplets that dispersant injection would be of limited value (Paris et al. 2012; Aman et al. 2015). Others present different models that give millimeter sized droplets for untreated oil and significant effect of dispersant injection (Zhao et al. 2014). The Bureau of Safety & Environmental Enforcement (BSEE) and other decision makers, such as National Oceanic and Atmospheric Administration and the U.S. Coast Guard, would benefit from the availability of proven, accurate monitoring methods on the key parameters of oil droplet and gas bubble size.

The size of oil droplets from deep-water releases is important for both the fate and environmental effect of the released oil, and the success of the various countermeasure techniques. Releases similar to DWH could form relatively large oil droplets (multiple mm), which rapidly rise through the water column to form thick slicks on the surface, potentially very near the source. On the other hand, smaller oil droplets (< 500 µm) rise more slowly and can stay suspended in the water column for days to weeks, allowing processes such as microbial degradation to act upon the droplets (Brakstad et al. 2015). The basic idea of subsea dispersant injection (SSDI) is to reduce the interfacial tension (IFT) of the oil which will produce significantly smaller droplets. This may offer several advantages. Firstly, it reduces buoyancy, so droplets rise more slowly and are more susceptible to dissolution of the water soluble components present in the oil. Secondly, degradation by microorganisms may generate "flocs" of microbial biomolecules and oil degradation products (Hazen et al. 2010; Brakstad et al. 2015) that may have neutral, or even slightly negative, buoyancy (Passow et al. 2012) as an intermediate stage before further mineralization of the oil droplets. Finally, the oil that makes it to the surface can generate very thin and wide oil films due to the horizontal spreading of small droplets. Such thin surface oil films might not form emulsions on the surface, but rather naturally be re-dispersed by waves within hours. This is in strong contrast to the thick surface oil slick formed by rapidly rising large oil droplets that usually emulsify and form very persistent slicks that could drift for weeks increasing the likelihood of shoreline impact. This difference in persistence between thick emulsifying (> 0.2 mm) and thin non-emulsifying (< 0.1 mm) surface oil films has been observed in several experimental subsurface oil releases and real incidents (Rye et al. 1996, 1997).

2.1 Measurement Challenges

Particulate material, including particulate pollutants, is often fragile and will change in size if removed from its environment during sample collection. Thus, there is a critical need for accurate in-situ measurements of the concentration and size distribution of particulates, whether in the form of oil droplets, gas bubbles, plankton, marine snow, or other types of suspended material. In the case of a subsea blowout, knowledge of the oil droplet size at the release point is critical in determining the fate and extent of the oil released into the environment due to the tight coupling between droplet size, transport and degradation.

The challenge in obtaining such measurements is to address the large range of particle sizes, concentrations and materials present in polluted seawater. The size range of suspended particles relevant to marine pollution spans from nano-pollutants and bacteria up to multi-millimeter oil droplets or zooplankton. This range cannot be covered by one instrument alone and therefore in-situ monitoring must often constitute a suite of instruments, each using different techniques to capture information within a relative narrow size range. Laser diffraction is adopted by the commonly used Laser In-Situ Scattering and Transmissometry (LISST)-100 (Agrawal and Pottsmith 2000) and provides a good mechanism for undisrupted in-situ measurements. However, these measurements are restricted to particles less than 500 µm in diameter (Davies et al. 2012).

High concentration also poses a challenge for measurements in locations with acute ambient marine pollution ranges, where the concentrations near the source are much higher than the typical concentrations of suspended particles that suit the design of standard instruments, such as the LISST-100. In the case of a subsea blowout, challenges associated with large volume concentrations can be overcome by effectively increasing the height of measurement above the release plume to enable sufficient dilution. This approach is adapted in small-scale experimental releases such as those reported by Brandvik et al. 2013. However, this approach necessitates a significant experimental down-scaling at the point of release so that the droplet sizes and concentrations fall within the measurable range of the LISST-100. The real-world conditions of a blowout generate a need to extend droplet measurements to larger sizes and higher concentrations so that data suitable for response decision making are available.

Imaging, whether through holography or standard lens-based systems, is currently the only method that permits easy individual particle classification, since acoustic methods are limited to coarse or bulk statistics of the measured particle populations (Thorne and Hanes 2002; Thorne and Buckingham 2004). Conventional, lens-based imaging of suspended particles often suffers from limitations related to depth-of-field, particle occlusion, and perspective errors. It is these errors that were overcome by the use of holographic imaging, which effectively re-focusses identified particles during post-processing (Owen and Zozulya 2000; Graham and Nimmo-Smith 2010; Davies et al. 2015). Digital in-line holographic particle imaging is adopted by the commercially available LISST-Holo (Graham and Nimmo-Smith 2010), and has enabled the extension of the 500 µm limit of the LISST-100 to provide accurate measurements of oil droplets of larger droplets. The adoption of the LISST-Holo enabled new experiments of low energy and low concentration releases, and an assessment of dispersant effectiveness under these conditions, which was not previously possible using only the LISST-100. While the LISST-Holo has provided a step forward in our ability to monitor droplets surrounding blowouts, the usable upper size limit for automatically processed images is approximately 2 mm due to over-segmentation of large particles during reconstruction and binerization (Davies 2015) and the instrument struggles in high concentrations. Under-sampling is also a challenge for measurements of large droplets, as only one or two droplets of mm-scale can fall within the sample volume (4x6x50 mm) at any one time. In addition, the path reduction module (which reduces the sample volume to 4x6x25 mm) is required to reduce the likelihood of overlapping particles, but its use further exacerbates the problem of under-sampling.

When concentrations are high and droplet sizes are large (mm-scale), the advantages of the long path length and small pixel size of the LISST-Holo (or other holographic systems) are reduced. SINTEF's Silhouette Camera (SilCam) has been developed in-house within the department of Environmental Technology, initially to measure large particulate pollutants in seawater. The system has been used both in large-scale experimental subsea releases of oil and gas, and in the field to quantify the distribution of suspended material such as zooplankton, large phytoplankton, mineral grains and marine snow. Images are analyzed to provide size distribution and concentrations spanning from ~100μm to several cm in length, and an approach utilizing a Deep Convolutional Neural Network is used to identify the type of particle, be it a copepod, diatom chain, marine snow, oil droplet or gas bubble, etc. True, in-focus particle images are recorded in color directly, so minimal processing is needed. These images look very much like microscope images (albeit in a lower magnification). A typical image (of 15MB) is processed in about 0.7 seconds (dependent on concentration) to retrieve a particle size distribution, concentration and classified particle types within the image.

In summary, many techniques are available for quantification of in-situ suspended particles, but many of these struggle with challenges specific to monitoring acute releases of polluting material (Table 1), as is the case for subsea blowouts.

Table 1. Summary of most commonly used techniques for in-situ quantification of marine suspended particles

LISST-100 (laser diffraction)	- Size range 2.5-500 µm - Inverted optical signal cannot distinguish particle types - Computationally, light enables real-time data processing and display
LISST-Holo (holographic imaging)	- Typical size range 25-2000 µm - Can distinguish particle types from geometrical properties - Cannot distinguish between oil and gas - Computationally heavy post-processing
Standard Cameras (or video analysis)	- Typical size range 100-20000 µm - Heavily affected by errors in focusing, depth-of-field and perspective (i.e. closer particles appear larger)
SINTEF SilCam	- Size range 28-12000 µm (BSEE Prototype 108-12000 µm) - Can distinguish particle types from geometrical properties - Can distinguish between oil and gas - Low noise-level images enables real-time processing and display
Acoustics	- Can measure larger volumes and particle sizes than optical methods - Size distributions can be estimated, but separation of particle types often limited to bulk particle statistics (i.e. d50) - Heavily dependent on calibration of inversion algorithms

2.2 Objective

The primary objective of the work conducted within this project has been to raise the Technology Readiness Level (TRL) of the SilCam to level 8 such that the system is verified for deep-sea deployment so that in the event of a spill, it could be considered as a viable option for subsea monitoring (Panetta and Potter 2016). A TRL 8 is achieved when the SilCam is ready for deployment during a subsea blowout, providing real-time information within a plume on:

- Separated oil droplet and gas bubble size distributions within the range of 108-12000 µm
- Independent d_{50} (median diameter) of oil droplets and gas bubbles
- Independent concentrations of released oil and gas
- Oil-gas ratio

To document the capabilities of the improved SilCam, large-scale experiments of combined releases of oil and natural gas were performed at the National Oil Spill Response Research & Renewable Energy Test Facility, Oil and Hazardous Materials Simulated Environmental Test Tank (OHMSETT) together with experiments of varying dispersant dosages.

3 Method & Experimental Setup

A summary of the parameter space and data collected to verify SilCam large-scale performance is presented in Table 2. In addition to the experiments, several runs were conducted for training purposes for users of the SilCam delivered to BSEE as part of the project (Figure 1). Table 3 summarizes all releases performed during the test period.

Table 2. Summary of experimental parameters

Total number of experimental runs	25
Total oil released during experiments	7,560 L
Total dispersant released during experiments	30.6 L
Total number of raw SilCam images	119,117silc files
Total data volume	1,786 GB
Nozzle diameters	25; 50 mm
Gas to Oil Ratios (GORs)	0; 0.5; 1
Dispersant to Oil Ratios (DORs)	0; 0.1
Release rates (of oil component)	60; 120; 240 L/min
Oil type	Oseberg blend
Dispersant type	Corexit C9500
Gas type	Air

Figure 1. Setup and training of the prototype SilCam delivered to BSEE at OHMSETT.

Table 3. Description and schedule of releases performed during April 2018

Experiment ID	Description	Date Conducted
RUN000	GAS & WATER	Wednesday 11th
RUN001	GAS & WATER	Thursday 12th Morning
RUN002	OIL	Thursday 12th Afternoon
RUN003	OIL	Friday 13th Morning
RUN004	OIL & DISPERSANT	Friday 13th Afternoon
RUN005	OIL	Tuesday 17th Morning
RUN006	OIL & DISPERSANT	Tuesday 17th Afternoon
RUN007	OIL & DISPERSANT	Tuesday 17th Afternoon
RUN008	OIL & DISPERSANT	Wednesday 18th Morning
RUN009	OIL & DISPERSANT	Wednesday 18th Morning
RUN010	OIL & DISPERSANT	Wednesday 18th Afternoon
RUN011	GAS & WATER	Thursday 19th Afternoon
RUN012	GAS & WATER	Thursday 19th Afternoon
RUN013	GAS & WATER	Thursday 19th Afternoon
RUN014	GAS & WATER	Friday 20th Morning
RUN015	OIL & DISPERSANT	Friday 20th
RUN016	OIL & DISPERSANT	Friday 20th
RUN017	OIL	Monday 23rd
RUN018	OIL	Monday 23rd
RUN019	SilCam Training	Tuesday 24th
RUN019	SilCam Training	Tuesday 24th
RUN021	GAS & WATER	Wednesday 25th Morning
RUN022	OIL	Wednesday 25th Afternoon
RUN023	SilCam Training	Wednesday 25th Afternoon
RUN024	OIL	Thursday 26th Morning
RUN025	GAS & WATER	Thursday 26th Morning

3.1 Experimental Design for Testing Large-Scale Performance

Experimental simulations of subsea oil and gas blowouts usually require a tall basin, at the bottom of which is a release system that can control rates of oil and gas through a nozzle of known dimensions. At a suitable height above the release is a monitoring device for characterizing oil and gas size distributions the oil-to-gas ratio. In this case, the only monitoring device is the SilCam, as no other suitable technology was available. This poses a challenge for inter-comparison of the results obtained against other monitoring methods. Thus, knowledge of what is released and what is present at the point of measurement is important. For a vertical release, it can be assumed that the gas-to-oil ratio and oil and gas sizes are relatively homogeneously distributed throughout the plume cross-section, with concentration decreasing with height above the release. Thus, averaging a point measurement in the center of the plume over a sufficient period of time is sufficient to obtain representative data.

The main challenge using the OHMSETT facility for simulating subsea blowouts is the limited water depth (effective depth 2.5 m). For large release rates, this provides a challenge for all available monitoring methods due to over-concentration. However, the depth limitation has been partly circumvented by mounting the release and monitoring equipment on two moving bridges (one for the release arrangement and one for monitoring instruments), which are set a fixed distance apart. This tilts the plume and provides a mechanism for effectively extending the 'height' or distance from the release point such that sufficient dilution of the plume has occurred at the monitoring location.

A schematic overview of the experimental setup is shown in Figure 2 and an annotated photograph in Figure 3.

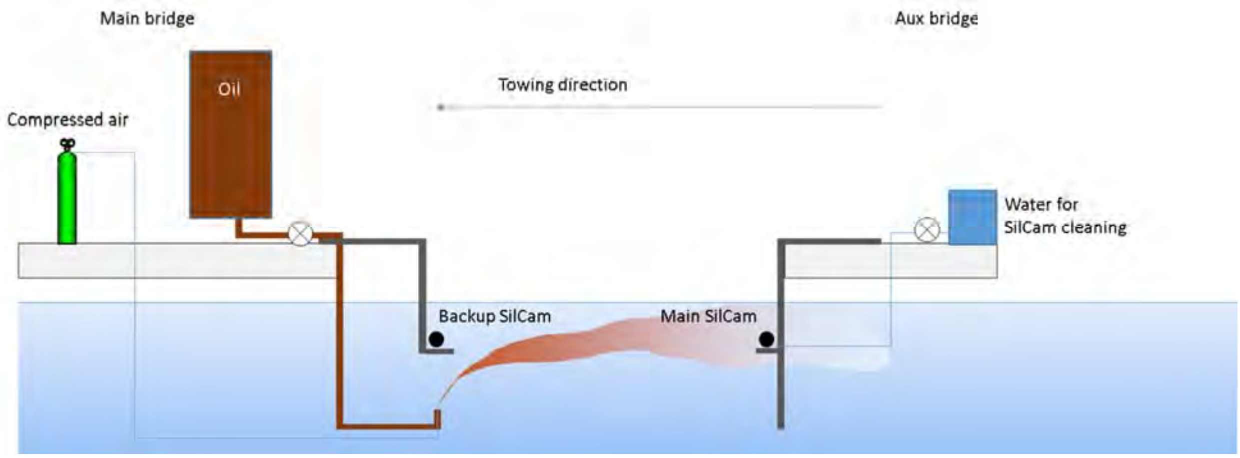

Figure 2. Schematic overview of experimental setup.

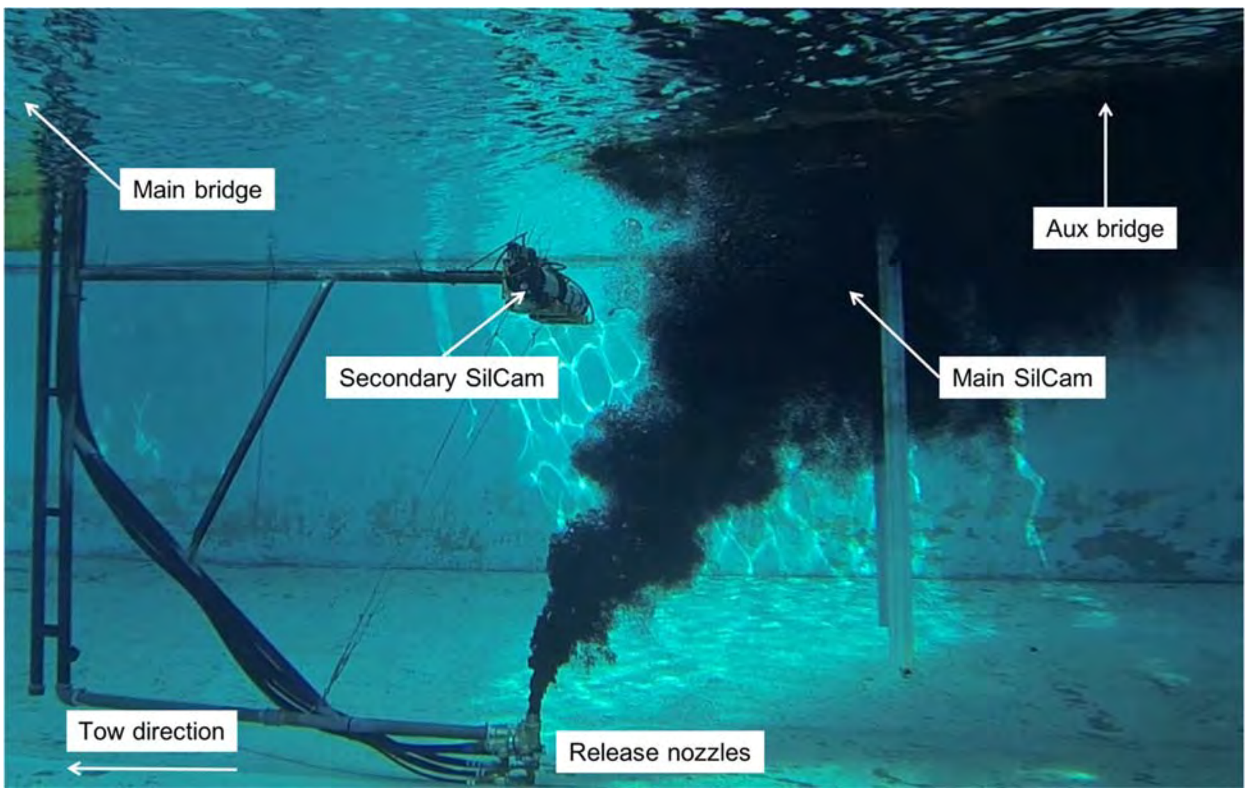

Figure 3. Annotated photograph during an experimental run of undispersed mixed oil and gas.

A disadvantage with the tilted plume approach is that size fractionation of the droplet sizes will occur after some distance from the release point, where the most buoyant droplets escape from the top of the tilted plume. It is therefore important that the size fractionation is considered when interpreting the results. Loss of large or highly buoyant droplets plays a less significant role in plumes where turbulent intensity is high in relation to the droplet size, and thus entrainment velocity is high enough to keep all droplets within the plume. To document the fractionation effect for mixed oil and gas releases, some experimental runs were performed with constant release conditions and varying tow speeds so that measurements through the entire cross-section of the plume could be made.

3.2 Release Nozzle

Three release nozzles were mounted side by side in a configuration that enabled oil, gas and dispersant to be injected into the flow prior to the release nozzle (50mm, 25mm and 32mm), as shown in Figure 4 (the 32mm nozzle was not used). For gas-only experiments, water was substituted for oil.

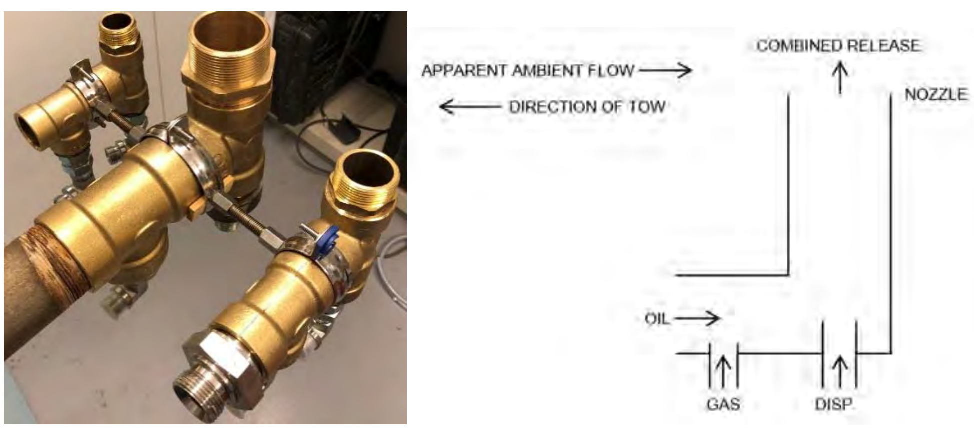

Figure 4. Photograph of the three-nozzle system and schematic of the release arrangement for each nozzle.

3.3 SilCam

The SilCam was used as the primary in-plume monitoring device during all experiments. An additional SilCam was mounted directly above the release to document any very large gas bubble that immediately escaped the plume during towing. This section outlines the main principles of the hardware and software design. A more complete documentation of the operation of the instrument has been provided to BSEE in the form of the *SilCam Operating Manual* (Appendix A), together with the prototype. A proposed *Silhouette Camera Subsea Dispersant Monitoring Plan* (Appendix B) for use and deployment of such a system in the event of a deep water oil release has also been provided to BSEE as part of this project.

While the SilCam can be configured with a magnification that can resolve as small as 28µm particles, the maximum size is also reduced because path length between the windows must also be reduced (to around 3-4mm). For a blowout scenario, it is more important to target measurements of the larger droplets and resolve the differences between undispersed and dispersed oil, as opposed to a measurement system that can only resolve droplet sizes after dispersant is applied. This is the motivation for the choice of magnification used in the BSEE prototype, which enables measurements from just over 100µm and a maximum path length of 40mm.

3.3.1 Hardware

The concept underpinning the SilCam hardware is relatively simple (Figure 5); a diffuse white backlight illuminates a sample volume of a finite path length, which is imaged using a telecentric lens-based camera. Short exposure times are necessary for fast-moving particles and are obtained by pulsing the light-emitting diode (LED) in an over-drive mode to give a bright and short flash. If necessary, this pulse can also be configured asynchronously from the camera shutter to make exposure times shorter than the minimum shutter speed for the camera. The result of this configuration is an image where all particles in the sample volume are in focus and where the pixel size is constant for all locations within the image. Transmittance information in red, green and blue color channels is obtained and used to help identification of particle type in subsequent analysis.

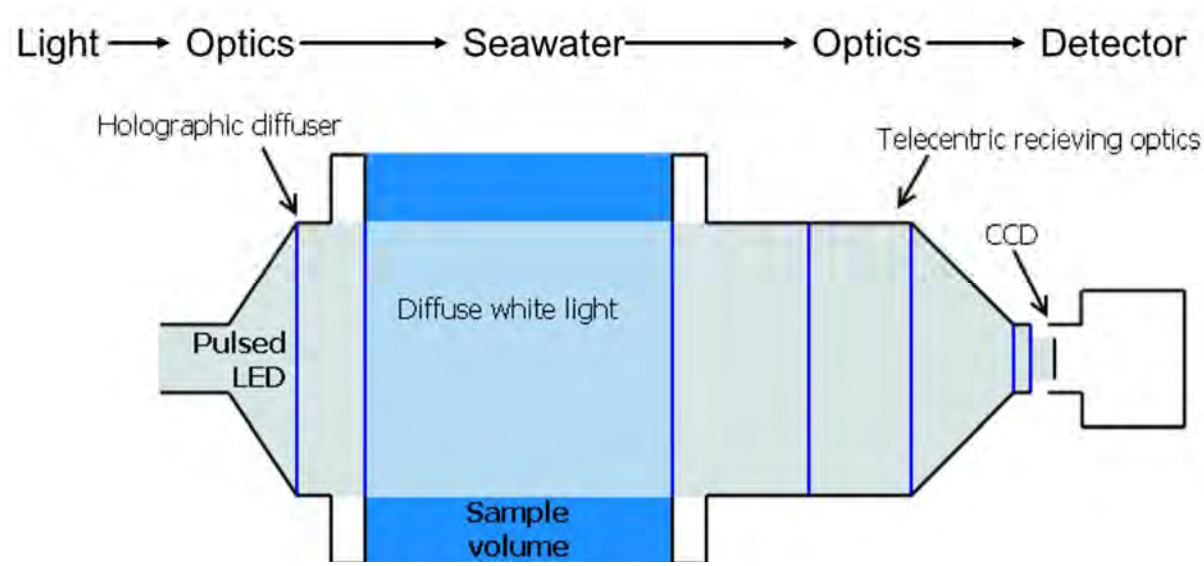

Figure 5. Schematic diagram of SilCam hardware (from Davies et al. 2017). CCD: Charge-Coupled Device.

The system is shown in Figure 6. It consists of three housings: 1) subsea linear actuator for adjusting the length of the sample volume; 2) illumination housing; 3) camera housing. These housings are mounted in-line on a single bracket. Additionally, an in-situ cleaning system is mounted on the same bracket, directing cleaning nozzles towards the windows of the illumination and camera housings. When deployed, this should be mounted upside-down than as in the figure, such that the rising droplets enter the sample volume without disruption from the mounting bracket.

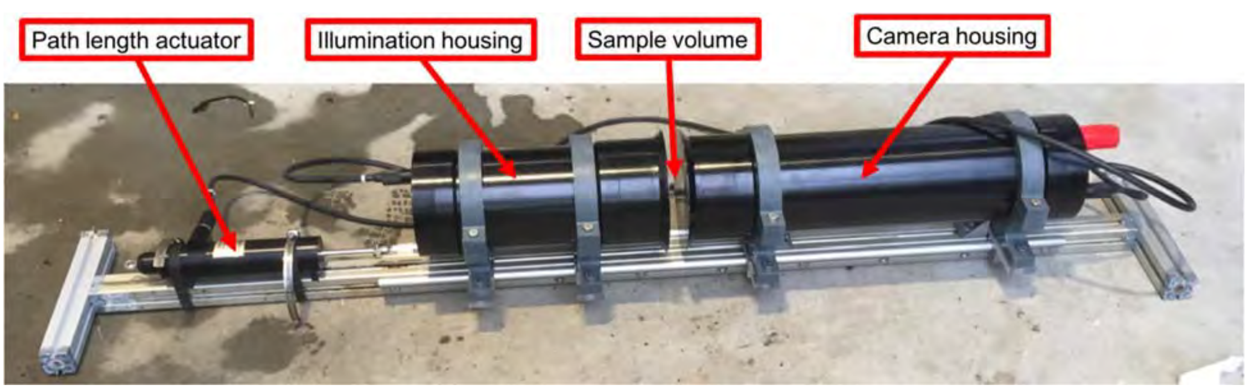

Figure 6. Annotated photo of the SilCam. Note: the instrument is standing upside-down to that which would be usually the case for monitoring within a buoyant plume.

The project's first hardware improvement was adding a software controlled actuator for adjusting the SilCam path length of the sample volume. The actuator was tested as part of SilCam experimental work in December and has worked well in controlling the sample volume size which can be seen in Figure 6 above.

An in-situ cleaning system was also added. The nozzles are mounted between the two housings of the SilCam, as indicated in Figure 7. For the OHMSETT testing, the water for in-situ cleaning is pumped from the auxiliary bridge but when Remotely Operated (Underwater) Vehicle (ROV) mounted, the pumping will come from the ROV. A photo of the mounting bracket that contains the cleaning nozzles is shown below.

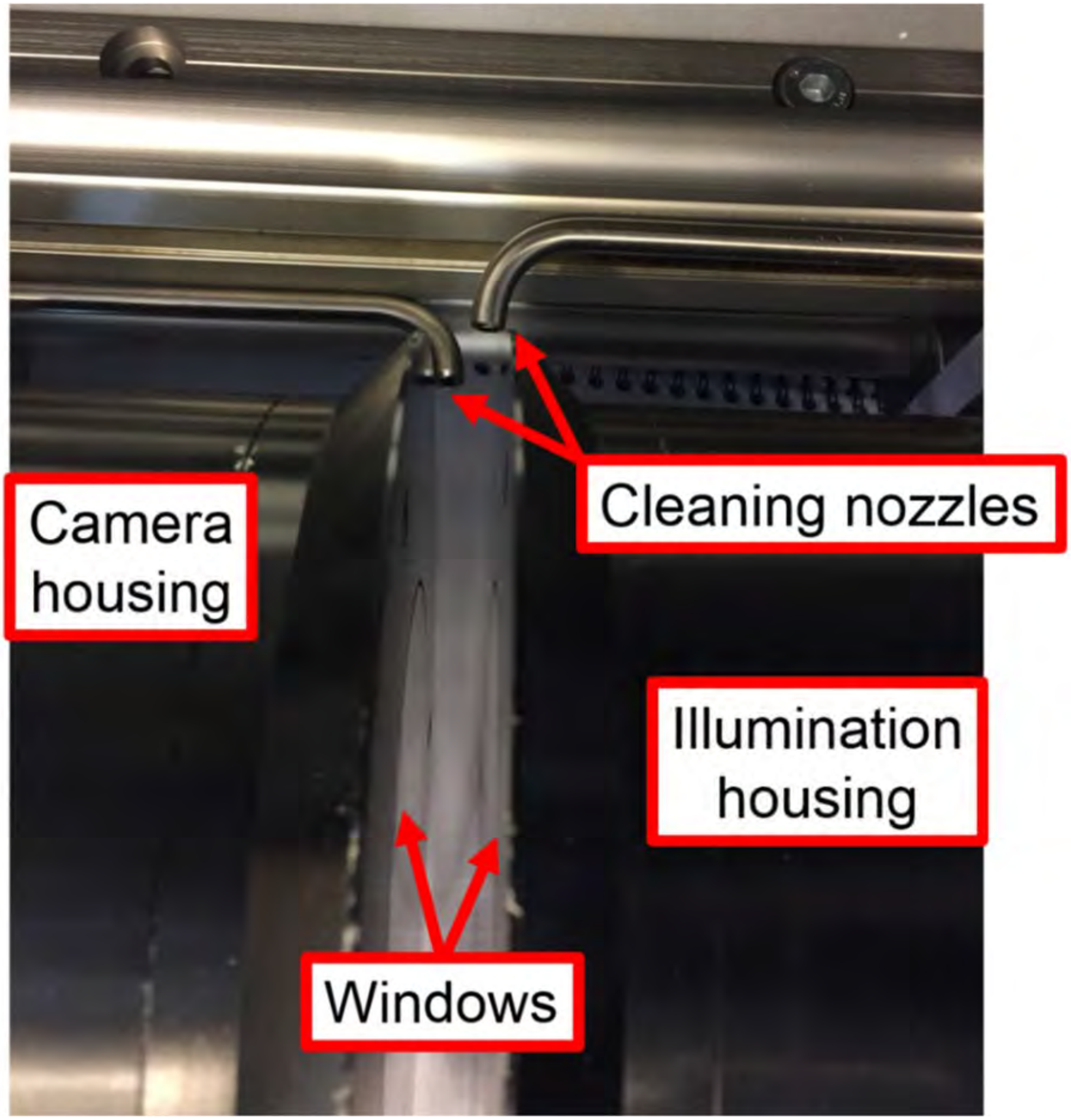

Figure 7. Photograph of mounting bracket containing cleaning nozzle system.

The final hardware improvement made during the project was developing an internal triggering unit for controlling the LED light source has now been tested on a number of SilCam units (Figure 7). Using this new, internal triggering unit means that the complete SilCam system is now contained in two housings without the need for a deck-box, and thus has enabled the instrument to be deployed from an ROV (Figure 8), with power and data being cabled to the ROV.

Figure 8. Photographs of the SilCam mounted on the front of an ROV.

The updates have reduced the number of cables and top-side components that need connecting prior to deployment of the instrument. There is now only one cable connecting the instrument to the deployment platform – whether it is a laptop and power supply in a laboratory, or a port on an ROV. This single cable is used for power, data, and communicating with the path length adjustment actuator.

3.3.2 Software

A series of software updates have been made during the project which build upon the approach outlined by Davies et al. 2017. The approach to analysis is now improved to provide real-time statistics on oil and gas size distributions and GOR and can be controlled by a graphical user interface. The user interface can also be used to generate summary statistics that can be exported to Excel, and summary figures that can be used directly in reports. The version of the software provided with the prototype is updated so that the differentiation (Step 9 in Figure 9) of oil and gas is now performed using a Deep Convolutional Neural Network using TensorFlow, (Abadi et al. 2016). This is a method that relies on a database of 'known' particles types, which is used to train the network. Thus, the accuracy of the differentiation is dependent on the training set used.

The training data used for the neural network analysis presented here was based on historical data collected in the SINTEF Tower Basin – in future this could be updated to include the new 2018 OHMSETT data as part of the training database. The use of a convolutional neural network is faster and more flexible than that published by Davies et al. 2017 and maintains a high accuracy. It also enables removal of non-oil or gas particles (the Davies et al. 2017 method assumed that only oil or gas are present within the same volume, which could be problematic in a real spill with other material in the water column such as suspended sediments).

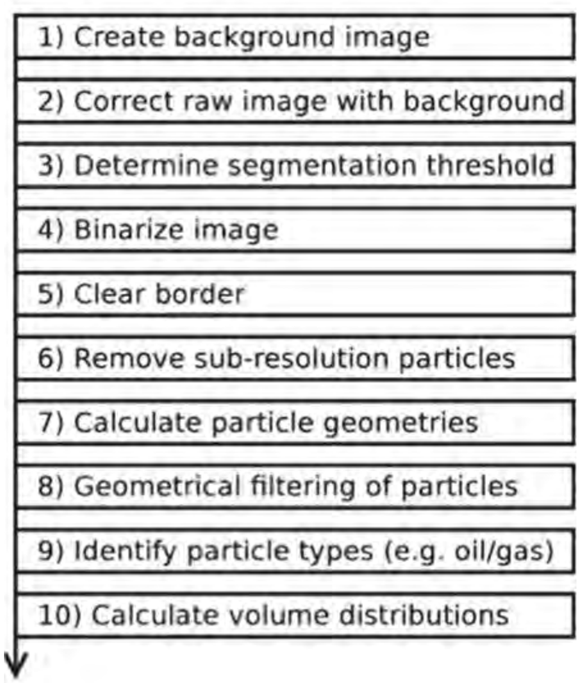

Figure 9. Basic analysis workflow from Davies et al. 2017.

For calculating properties of oil and gas, particles with a solidity less than 0.95 are removed to avoid miss-calculation of overlapping particles, and particles with a deformation less than 0.3 are removed because oil and gas will split if deformed more than this. A deformation of more than 0.3 corresponds to droplet Weber numbers that are known to be unstable and therefore subjected to droplet breakup (Hinze 1955). Solidity is a geometrical parameter that measures how close an object area is to its convex hull – the convex hull being the area that would be filled by a particle without any indentations. Thus, solidity provides a means of removing overlapping objects when analyzing droplets which should not contain any indentations.

An outline of the updated processing workflow is shown in Figure 10. This workflow makes use of multicore processing to speed up analysis time, which scales by the available number of central processing unit (CPU) threads on the computer being used.

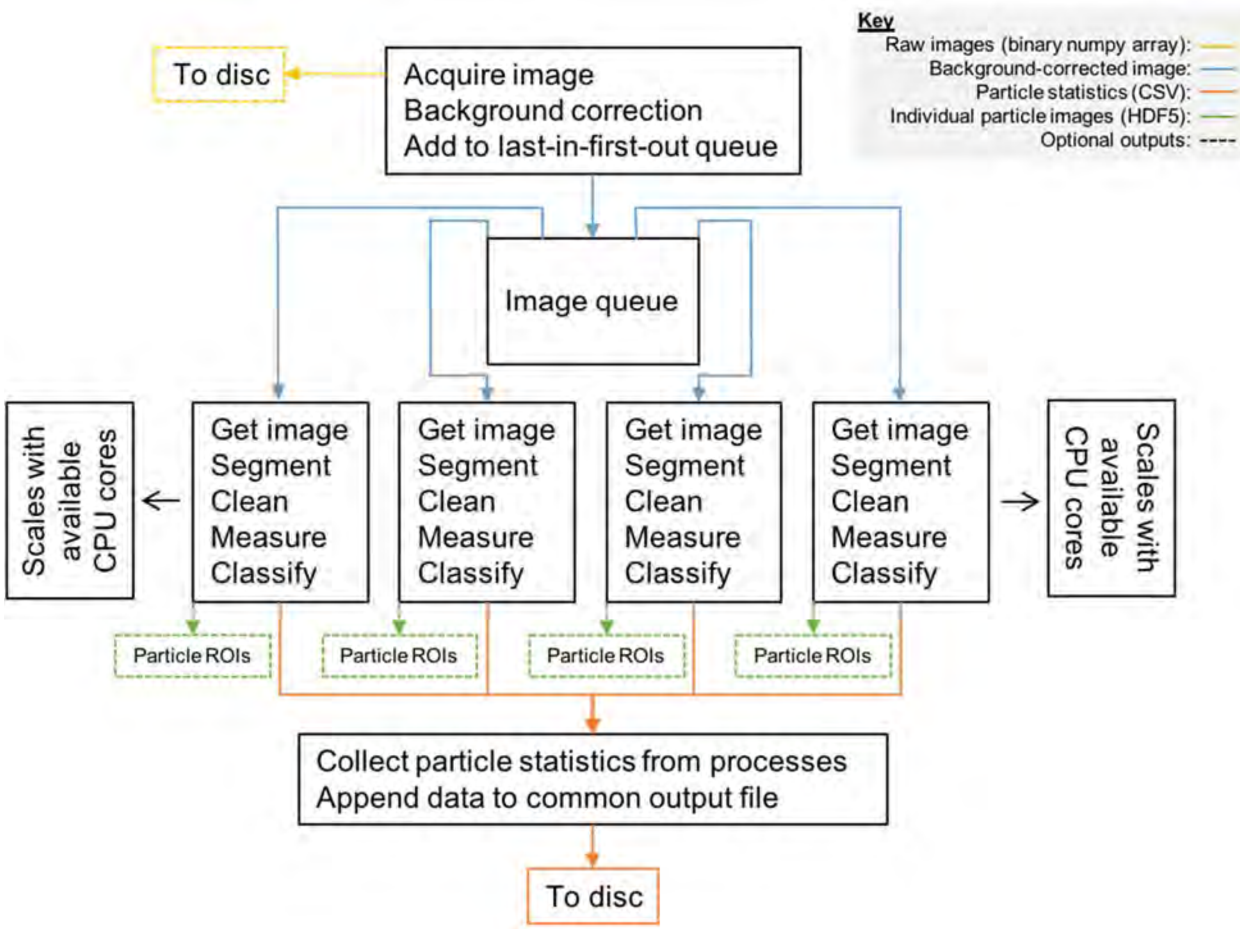

Figure 10. Overview of workflow for SilCam analysis.

A prototype graphical user interface (GUI) for the SilCam python package (*PySilCam*) has been constructed to handle all aspects of data collection, processing and plotting, without the need for scripting or programming in order to operate the instrument. The priority has been to make this interface as simple to use as possible. It contains the following features:

- Acquisition of raw images from the SilCam (saving raw data is optional)
- Processing of raw data to size and classify particles

- Real-time processing of raw data (saving raw data is optional) that enables live plotting of oil and gas size distributions.
- Hypertext Transfer (or Transport) Protocol (HTTP) serving of processed data, including a live stream of oil and gas d50, which can be accessed by other devices via Standardized Wireless Local Networking (WiFi).
- Plot creations (summary figure of a dataset can be saved as a png file)
- Playback of raw data files
- Conversion of raw data files into bmp files
- Exporting of summary data to Excel

An example of statistics plotted when in real-time are shown in Figure 11. This example is of a gas release, without oil.

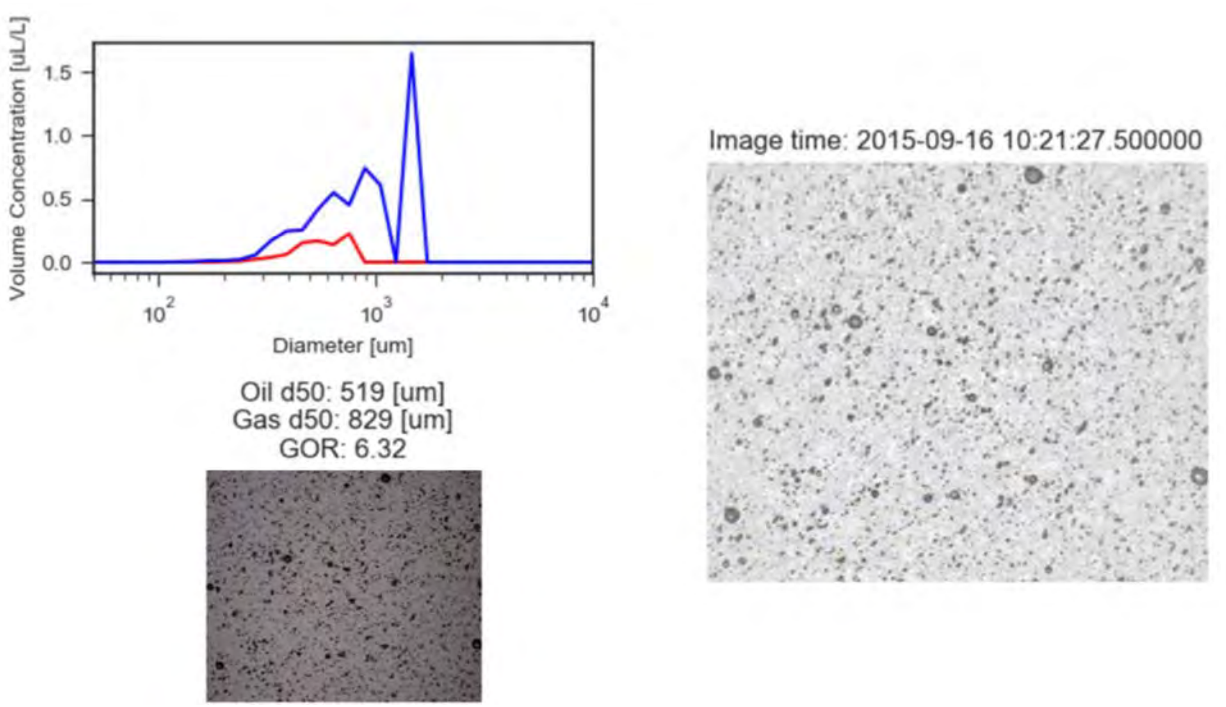

Figure 11. Example of live data displayed in the SilCam GUI. The top left plot shows the particle size distribution of gas in blue, and oil in red. The d50 of oil and gas and the GOR, is also printed in text underneath this plot. The statistics shown here are averaged over the period specified by the user (typically 30-seconds). The bottom left image shows a raw image (uncorrected). The right image shows the corrected image following background correction.

4 OHMSETT Tests, SilCam Training and Prototype Delivery

The SilCam Project experimental plan, SilCam training and prototype delivery were all completed during the team stay at OHMSETT from 9th to 26th April 2018. In all, 25 experiments were performed with varying release conditions (GOR, DOR, Nozzle diameter, Release rate) and utilizing SilCam apparatus for monitoring. A schematic overview of the experimental setup is shown in Figure 12 and Figure 13. A summary of the parameter space and data collected is presented in Table 4.

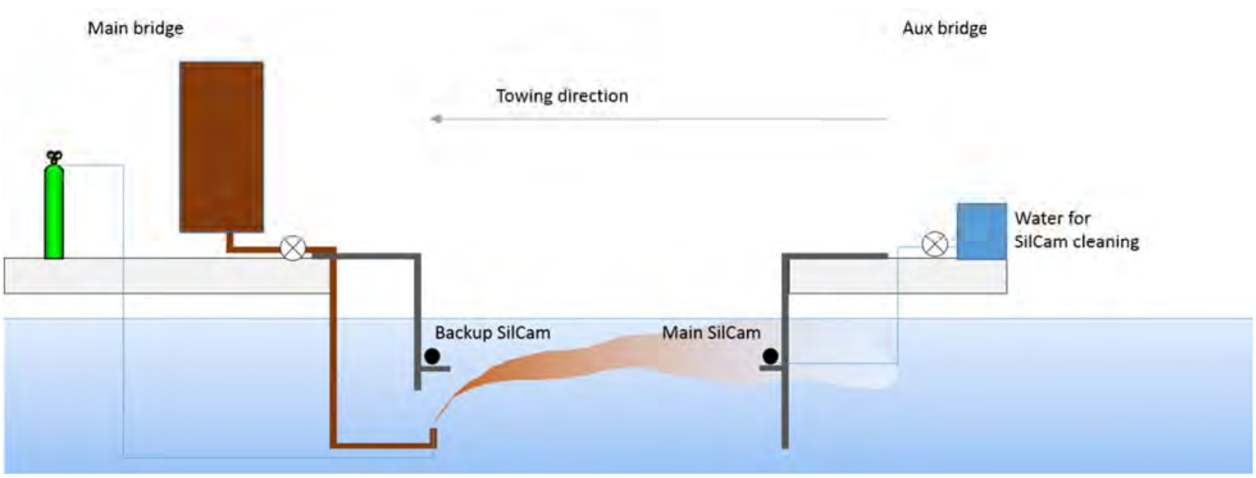

Figure 12. Schematic overview of experimental setup.

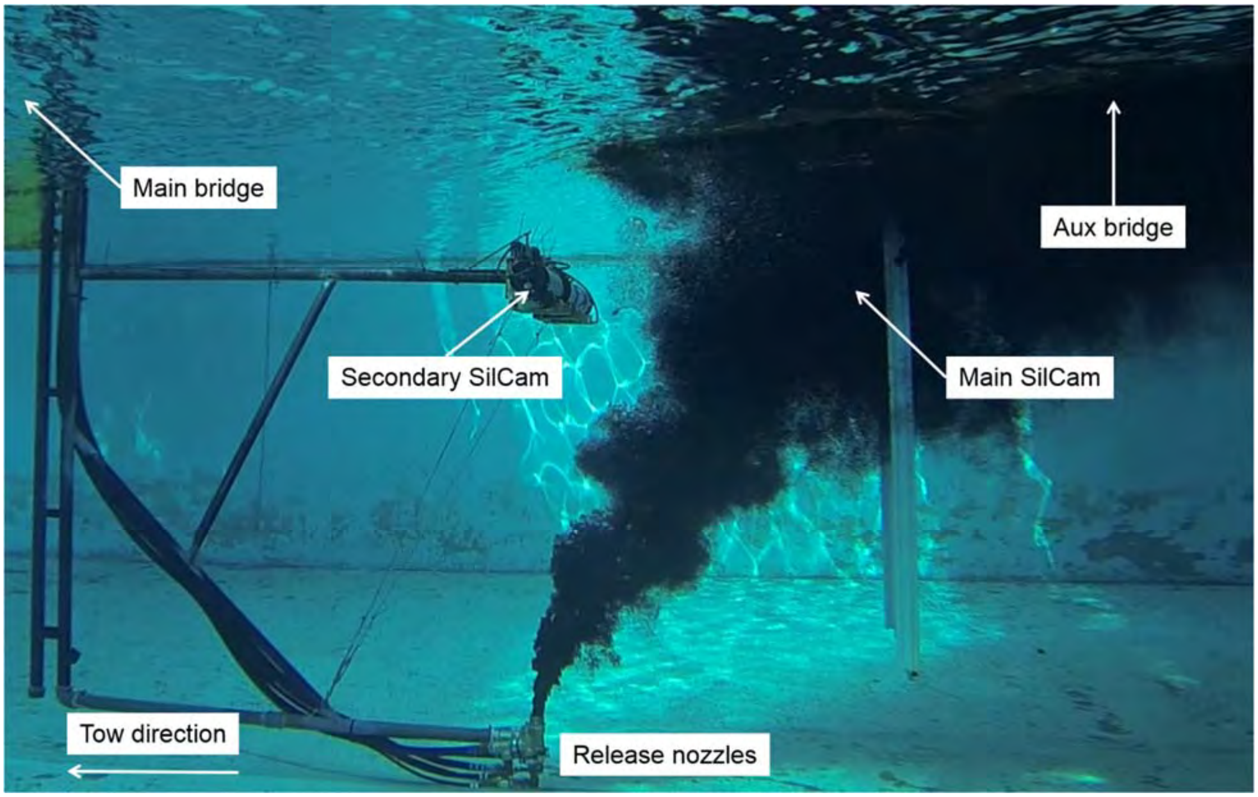

Figure 13. Annotated photograph during an experimental run of undispersed mixed oil and gas.

Table 4. Summary of experimental parameters

Total number of experimental runs	25
Total oil released during experiments	7,560 L
Total dispersant released during experiments	30.6 L
Total number of raw SilCam images	119,117silc files
Total data volume	1,786 GB
Nozzle diameters	25; 50 mm
GORs	0; 0.5; 1
DORs	0; 0.1
Release rates (of oil component)	60; 120; 240 L/min
Oil type	Oseberg blend
Dispersant type	Corexit C9500
Gas type	Air

In addition to the experiments, several runs were conducted for training purposes for users of the SilCam delivered to BSEE as part of the project (see Figure 1).

During the testing and training the SilCam ability to provide the following types of data key to the project were demonstrated as well as taught in training:

- Separated oil droplet and gas bubble size distributions within the range of 108-12,000 µm
- Independent d50 (median diameter) of oil droplets and gas bubbles
- Independent concentrations of released oil and gas
- Oil-gas ratio

Training of BSEE and OHMSETT personnel was conducted Tuesday 24th and Wednesday 25th of April 2018, beginning with an orientation classroom session followed by hands on training operating the SilCam to collect data. Training on the use of the SilCam software provided as part of the prototype to conduct data analysis after data collection was also provided. The use of both real-time data processing and post-processing were taught and trained to ensure both methods and their use were understood as part of the training.

A *SilCam Operating Manual* was shared with BSEE and OHMSETT staff and used during training. After feedback was incorporated, the manual was finalized and is attached to this report (Appendix A).

A generic monitoring plan for using a ROV deployed SilCam during an oil well blowout was also developed as part of the project. This document is intended to supplement existing industry guidance such as the American Petroleum Institute (API) subsea dispersant monitoring plan document (API TR 1152). The plan describes a new method of monitoring subsea dispersant efficacy using the Silhouette Camera (SilCam) by directly measuring oil and gas droplet size in the release plume near the point of subsea release. SilCam monitoring will allow direct subsea observation changes in the oil droplet size due to dispersant oil treatment and provide a method of ongoing assessment of subsea dispersant operations as well as provide opportunities to monitor gas subsea and to estimate the oil to gas ratio of the release. This new method can be used as a valuable supplement to indirect methods of subsea dispersant efficacy such as aerial photography, near surface Volatile Organic Compounds (VOC) monitoring or visual ROV camera observations. This *Silhouette Camera Subsea Dispersant Monitoring Plan* is also attached to the report (Appendix 2).

A SilCam prototype instrument with the needed cables for OHMSETT testing and ROV use was transferred to OHMSETT on Thursday April 26th 2018 with the specifications required in the project:

- Housings pressure-tested to 300 bar
- Communication & power cable for ROV interface
- Development version of the acquisition and processing software
- Measurable droplet size range: 108–12,000 µm

5 Results and Discussion

5.1 Historical Data

Historical data presented by Davies et al. 2017 demonstrates the ability of the SilCam to measure particle size distributions correctly by testing of spherical standards (Figure 14), and also to measure oil droplet size distributions on small scale, which correspond closely to that of the LISST-100 (Figure 15). It was also demonstrated that the SilCam could estimate GOR effectively on small scale (Figure 16). However, large-scale verification with mixed oil and gas remained necessary, and forms the need for the new data presented here.

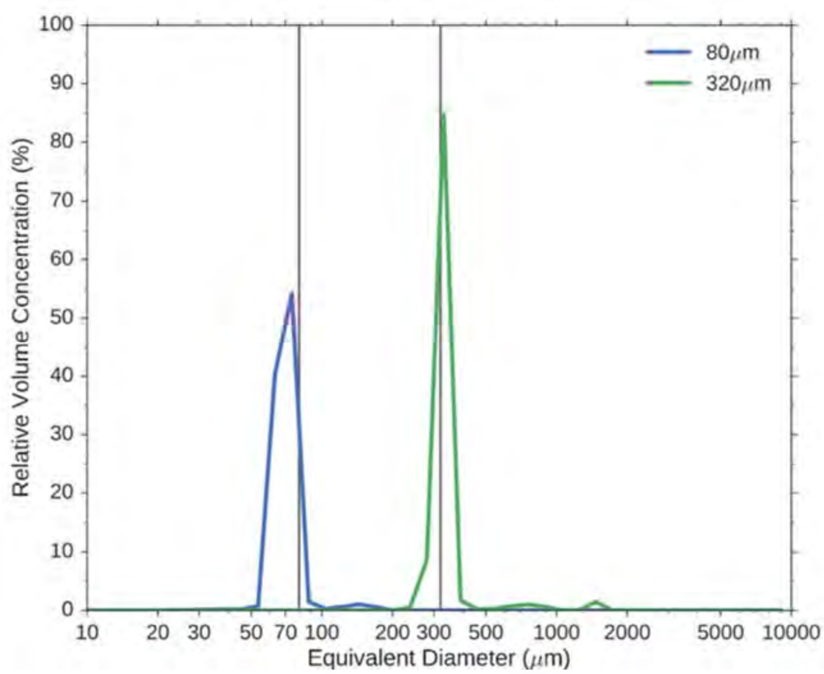

Figure 14. Measurements of suspensions of spherical standards of 80 μm and 320 μm. From Davies et al. 2017.

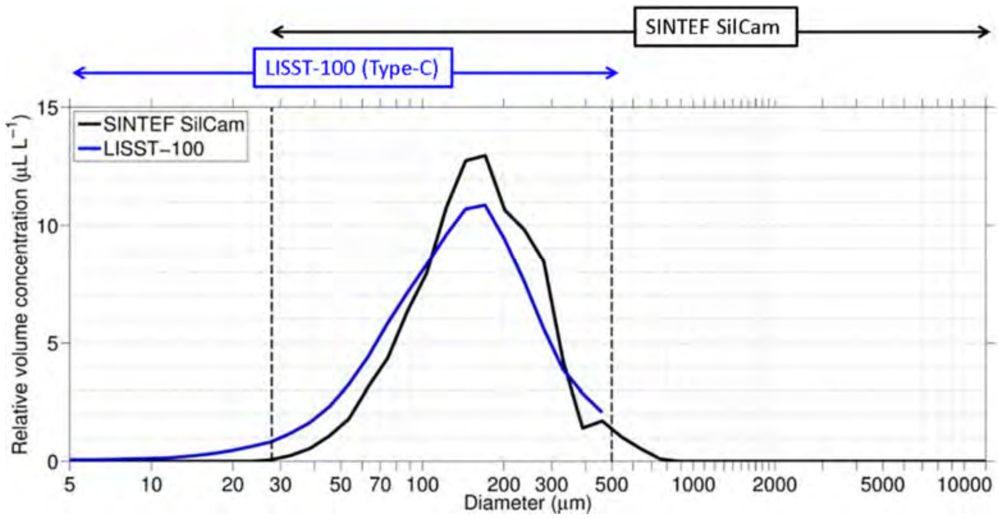

Figure 15. Oil droplet size distributions from the LISST-100 and SINTEF SilCam, while deployed alongside each other. The distributions presented are recorded over an identical 30-second period. Black dashed lines indicate the limits of the size classes that are that are common to both instruments. Figure from Davies et al. 2017. Note: the magnification of the SilCam used for subsea blowouts has a lower size limit of 108µm instead of 28µm, which is shown here.

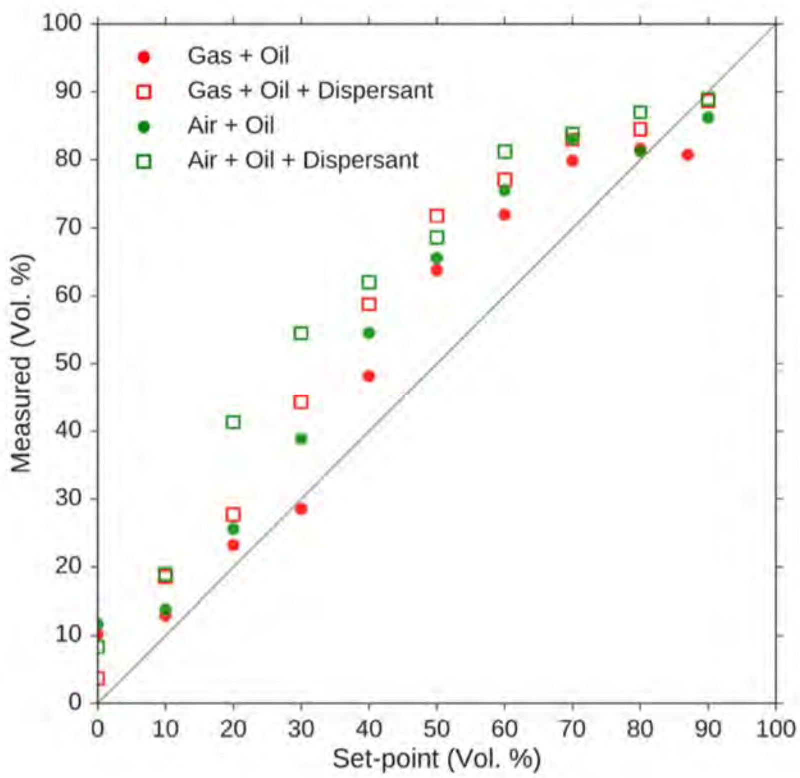

Figure 16. Comparison of released and measured gas percentage from small-scale mixed releases. These experiments were performed using stationary (vertical releases), where fractionation of large/small droplets was not a source of error. From Davies et al. 2017.

5.2 OHMSETT Data

In order to account for the fractionation of oil and gas droplets sizes that occurs as a result of tilting the plumes (due to the simulated cross-current e.g., Figure 3), some experimental runs were conducted with constant release conditions and varying the tow speed such that the position of the SilCam within the plume cross-section was varied. Thus, measurements of size distributions along the entire plume cross-section were obtained. Averaging the measurements through the course of a varying-speed run such as this provides data on the size distribution that would be independent of any fractionation due to differential rise velocities. This average is therefore indicative of the equivalent size distribution from the middle of a stationary plume. Figure 17 shows the oil and gas size distributions from such an experiment, together with some example images and statistics of the test. Results from this experiment show that the SilCam has detected multi-millimeter oil and gas droplets, which are close to that which is predicted by the Modified Weber droplet size model (Johansen, Brandvik and Farooq, 2013). The oil-gas ratio measured is also close to that which was released. This is presented as an oil-gas percentage (OGP) where 0% is oil only and 100% is gas only; 50% corresponds to a GOR of 1:1 – the use of percentage instead of GOR is because the GOR goes to infinity when there is only gas and no oil in the plume, and thus it is easier to constrain this information in the form of a percentage.

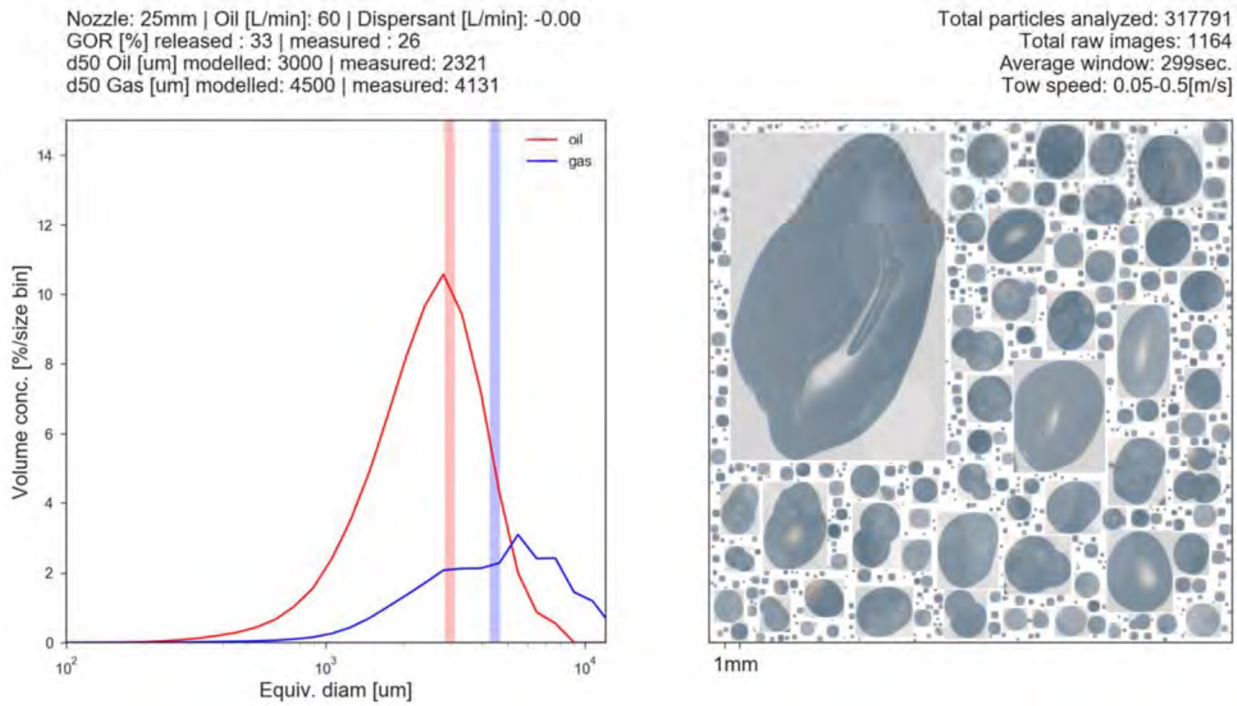

Figure 17. Summary of an experiment of varying speed and constant release conditions. The reported size distribution of oil (red) and gas (blue) is shown, with the predicted d50 from the Modified Weber droplet size models shown as vertical lines. A montage of particle images is shown on the right. This montage is auto-generated using a packaging algorithm that attempts to maintain the size distribution of particles to that which was measured, but in doing so, concentration (or separation between particles) is not represented.

Figure 18 shows a release of oil-only at large scale (240L/min and a 50mm release nozzle). These data are from a tilted plume, where the SilCam is positioned to intersect the plume trajectory (for the given tow speed and downstream distance) based on numerical modelling of the release. Thus, the results here may be subject to some error due to droplet size fractionation. However, they do indicate the ability of the SilCam to monitor and document this scale of release. Despite it being an oil-only release, some gas (5%) was measured by the system. This can be confirmed via visual inspection of the montage (right-hand plot of Figure 18), which shows some particles have transparent middle sections that are associated with gas bubbles. It could be possible that some gas was released at the start of this experiment, and thus recorded by the system.

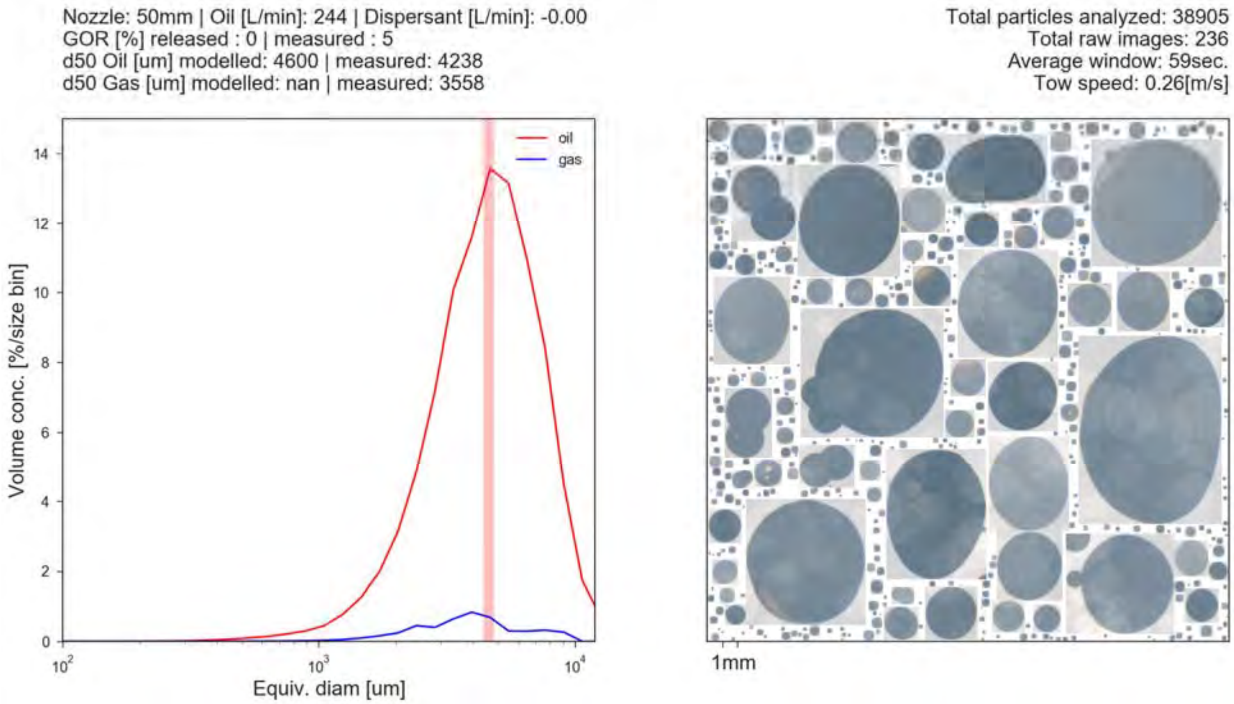

Figure 18. Summary of an experiment of an oil-only release from the 50mm nozzle at 240L/min. The reported size distribution of oil (red) and gas (blue) is shown, with the predicted d50 from the Modified Weber droplet size models shown as vertical lines. A montage of particle images is shown on the right. This montage is auto-generated using a packaging algorithm that attempts to maintain the size distribution of particles to that which was measured, but in doing so, concentration (or separation between particles) is not represented.

Figure 19 shows the SilCam results from the same oil release conditions as Figure 18, but with the addition of 1% dispersant immediately prior to the release. The addition of dispersant has resulted in a reduction in reported median oil droplet size from 4092µm down to 295µm. The SilCam in this case has reported 11% gas, mostly with sizes around 200µm. This is gas likely miss-classification of oil droplet as gas bubbles, indicating that the system may be subjected to an error in the oil-gas ratio of just over 10% in such a situation. The modelled d50 predicted was 310µm.

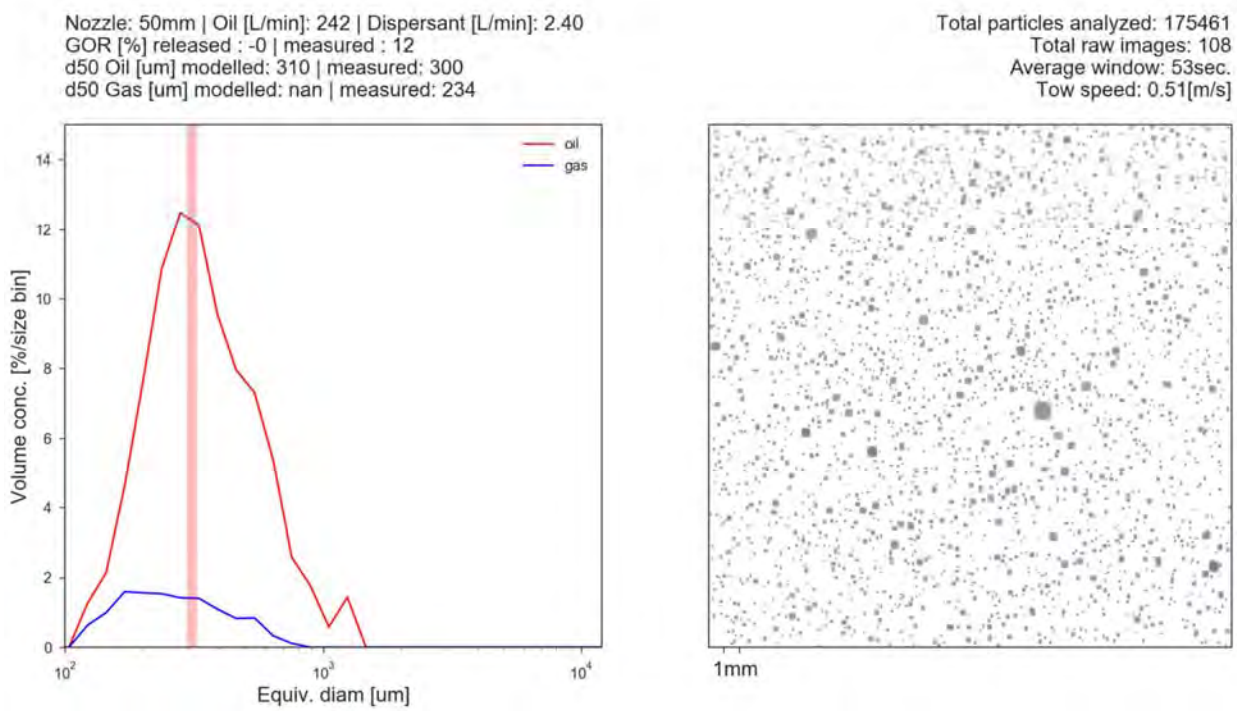

Figure 19. Summary of an experiment of an oil-dispersant release from the 50mm nozzle at 240L/min (1% dispersant injection). The reported size distribution of oil (red) and gas (blue) is shown, with the predicted d50 from the Modified Weber droplet size models shown as vertical lines. A montage of particle images is shown on the right. This montage is auto-generated using a packaging algorithm that attempts to maintain the size distribution of particles to that which was measured, but in doing so, concentration (or separation between particles) is not represented.

The ability of the SilCam to quantify gas bubble size distributions over a range of sizes is demonstrated in Figure 20 (with a d50 of 1094µm) and Figure 21 (with a d50 of 582µm). Here, gas was released together with water (as a substitute for oil) in order to maintain equivalent control of the gas bubble size distribution based on release conditions. The SilCam does falsely report some oil, but in both cases this error remains within 10%. The reported gas bubble d50s are in close agreement with that which is expected based on the Modified Weber model.

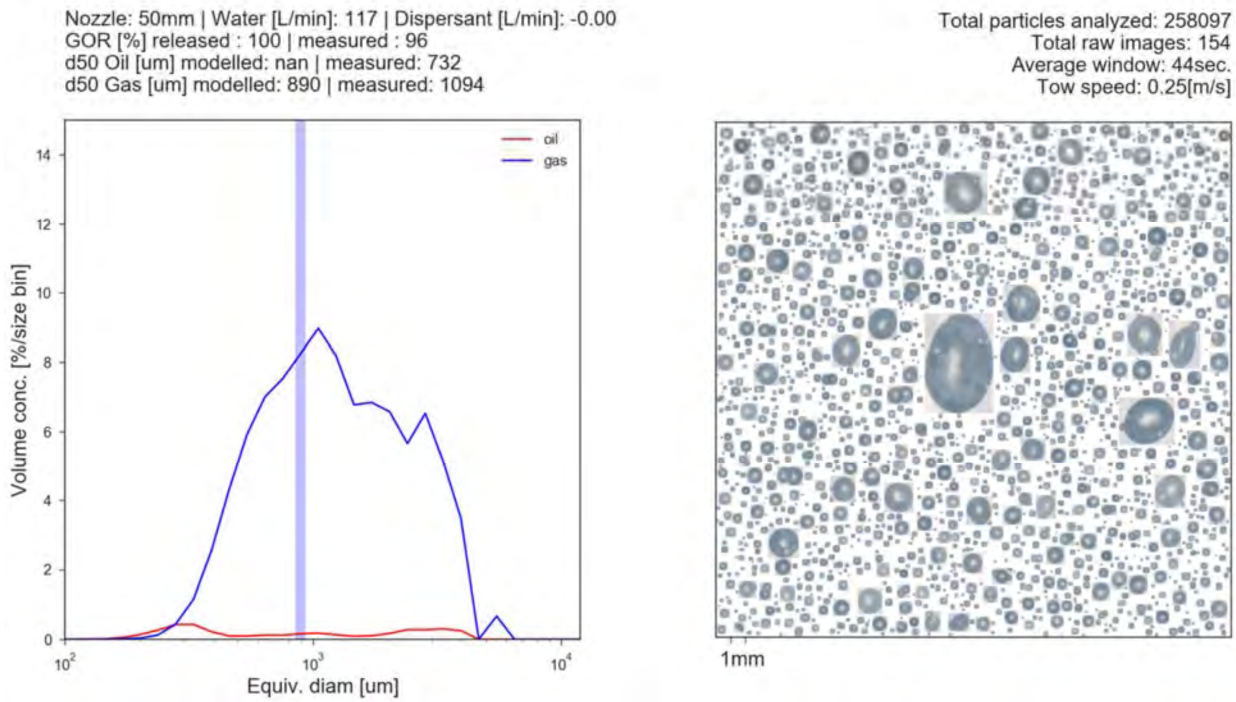

Figure 20. Summary of an experiment of a gas-water release from the 50mm nozzle at 120L/min (without dispersant injection). The reported size distribution of oil (red) and gas (blue) is shown, with the predicted d50 from the Modified Weber droplet size models shown as vertical lines. A montage of particle images is shown on the right. This montage is auto-generated using a packaging algorithm that attempts to maintain the size distribution of particles to that which was measured, but in doing so, concentration (or separation between particles) is not represented.

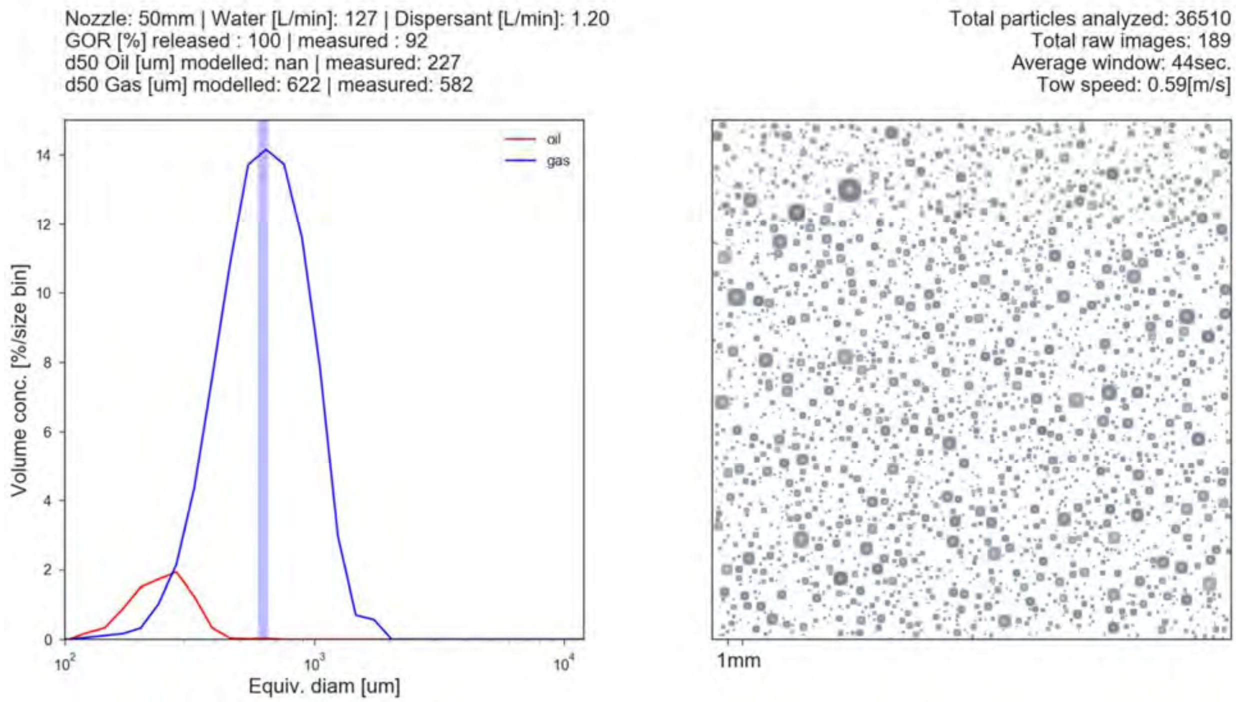

Figure 21. Summary of an experiment of a gas-water release from the 50mm nozzle at 120L/min (also with 1% dispersant injection). The reported size distribution of oil (red) and gas (blue) is shown, with the predicted d50 from the Modified Weber droplet size models shown as vertical lines. A montage of particle images is shown on the right. This montage is auto-generated using a packaging algorithm that attempts to maintain the size distribution of particles to that which was measured, but in doing so, concentration (or separation between particles) is not represented.

The final scenario demonstrated was that of mixed oil and gas of varying sizes. Figure 22 shows large oil and gas sizes (without dispersant injection) and Figure 23 shows small oil and gas sizes (with dispersant injection). A clear reduction in droplets sizes is evident when dispersant is applied. Here, it was challenging to optimize the tow speed and monitoring position to maintain the largest gas bubbles within the tilted plume prior to measurement. Thus, the under-reported gas concentration by the SilCam, can be explained by loss of large gas bubbles from the top of the plume. For example, this can be seen visually in Figure 3, where large gas bubbles are exiting the top of the plume before reaching the SilCam on the downstream side. The loss of gas in the dispersant release was less significant, and the reported oil-gas percentage is therefore closer to that which was released.

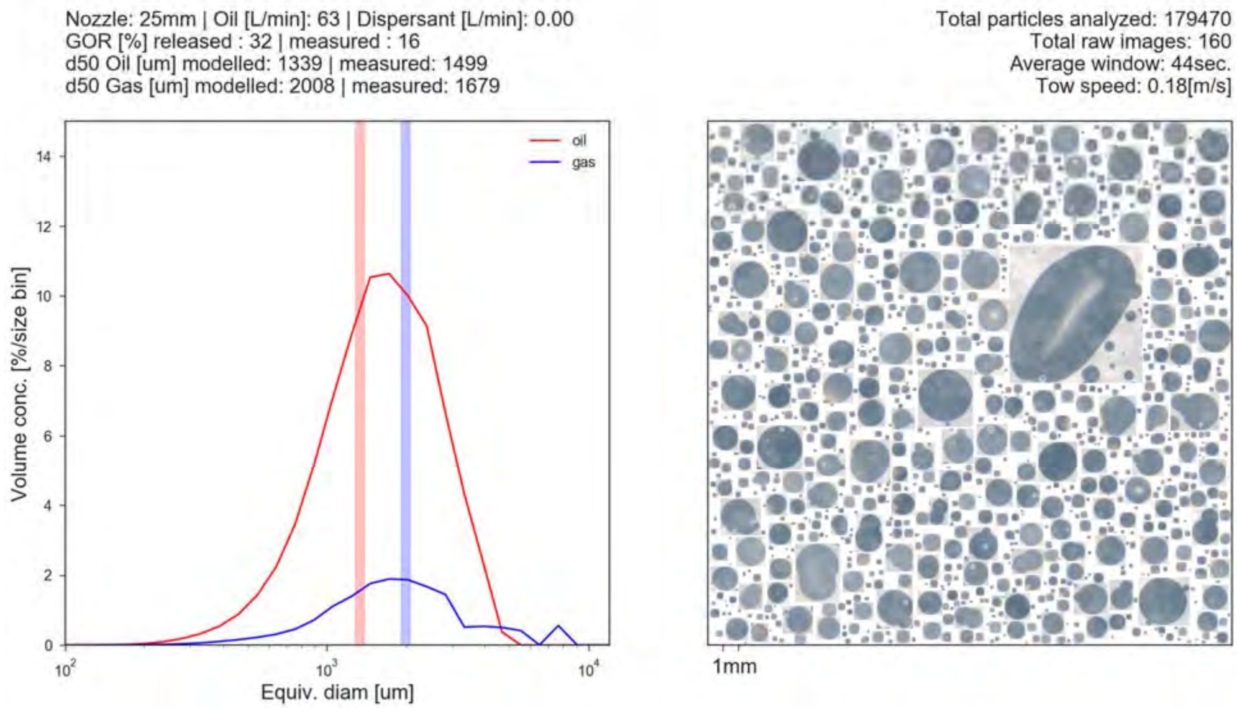

Figure 22. Summary of an experiment of large gas and oil droplets, released from the 25mm nozzle at 60L/min. The reported size distribution of oil (red) and gas (blue) is shown, with the predicted d50 from the Modified Weber droplet size models shown as vertical lines. A montage of particle images is shown on the right. This montage is auto-generated using a packaging algorithm that attempts to maintain the size distribution of particles to that which was measured, but in doing so, concentration (or separation between particles) is not represented.

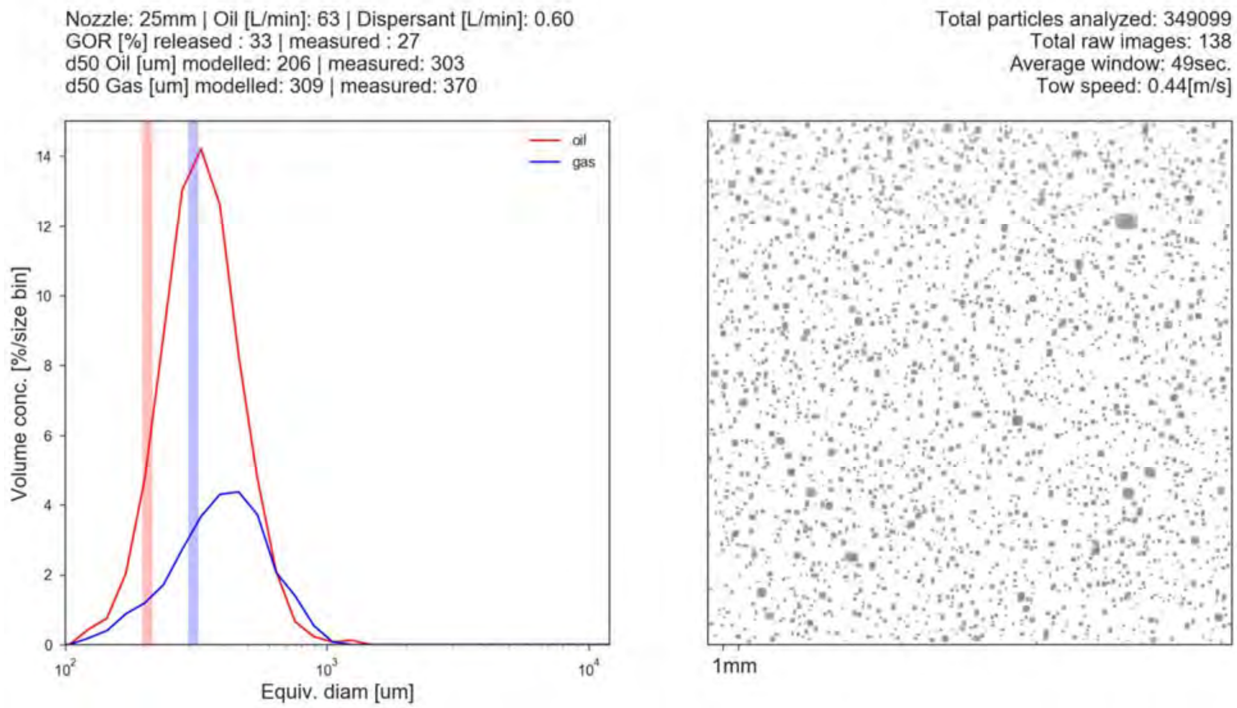

Figure 23. Summary of an experiment of dispersed gas and oil droplets, released from the 25mm nozzle at 60L/min (1% dispersant injection). The reported size distribution of oil (red) and gas (blue) is shown, with the predicted d50 from the Modified Weber droplet size models shown as vertical lines. A montage of particle images is shown on the right. This montage is auto-generated using a packaging algorithm that attempts to maintain the size distribution of particles to that which was measured, but in doing so, concentration (or separation between particles) is not represented.

The examples of experimental runs presented thus far demonstrate that the oil-gas ratio and droplet sizes follow explainable trend relating to the release conditions. There are some discrepancies in relation to the predicted droplet sizes in some situations, which can be explained by the challenges with aligning the tilted plume trajectories with the SilCam, especially in situations with mixed oil and gas. However, the experiments which profiled through the entire plume cross-section by varying the tow speed with constant release conditions, demonstrate very close agreement with the Modified Weber model for predicting droplet d50 (Figure 17). With this in mind, it is possible to summarize all experimental conditions tested by comparing the modelled and measured d50s (Figure 24). Here, the modelled d50s for a given release are presented as lines which span a range of values that could result from a 10% error in release conditions (nozzle size, release rate, GOR, IFT). The measured d50s by the SilCam are presented as simply the median droplet size from a period of up to 30s of stable release conditions. Outliers are mostly explained by mismatches in the plume trajectory and SilCam mounting position, in addition to escaping large droplets. For example, situations where there is significant loss of large bubbles or droplets from the plume will result in an overestimate of d50 of both oil and gas and a higher GOR if the measurement position was relatively high in relation to the plume centerline (i.e., in the "High GOR, Large d50" position indicated in Figure 25). The opposite is true if the measurements position was low in relation to the plume centerline (i.e., in the "Low GOR, Small d50" position indicated in Figure 25). Both of these uncertainties are addressed using the varying-speed experiments (Figure 17), where good agreement in d50 (modelled vs measured values were 3000µm vs 2321µm for oil and 4500µm vs 4131µm for gas) and GOR (modelled vs measured values were 33% vs 26%) was found. While such varying releases provide the most accurate data by removing the artifacts associated with size and GOR fractionation, it is not possible to run parallel release condition within one ‘run’ along the OHMSETT basin (i.e., one ‘run’ tests a single combination of release rate, DOR and GOR), and thus is not a convenient method for testing a wide range of release conditions.

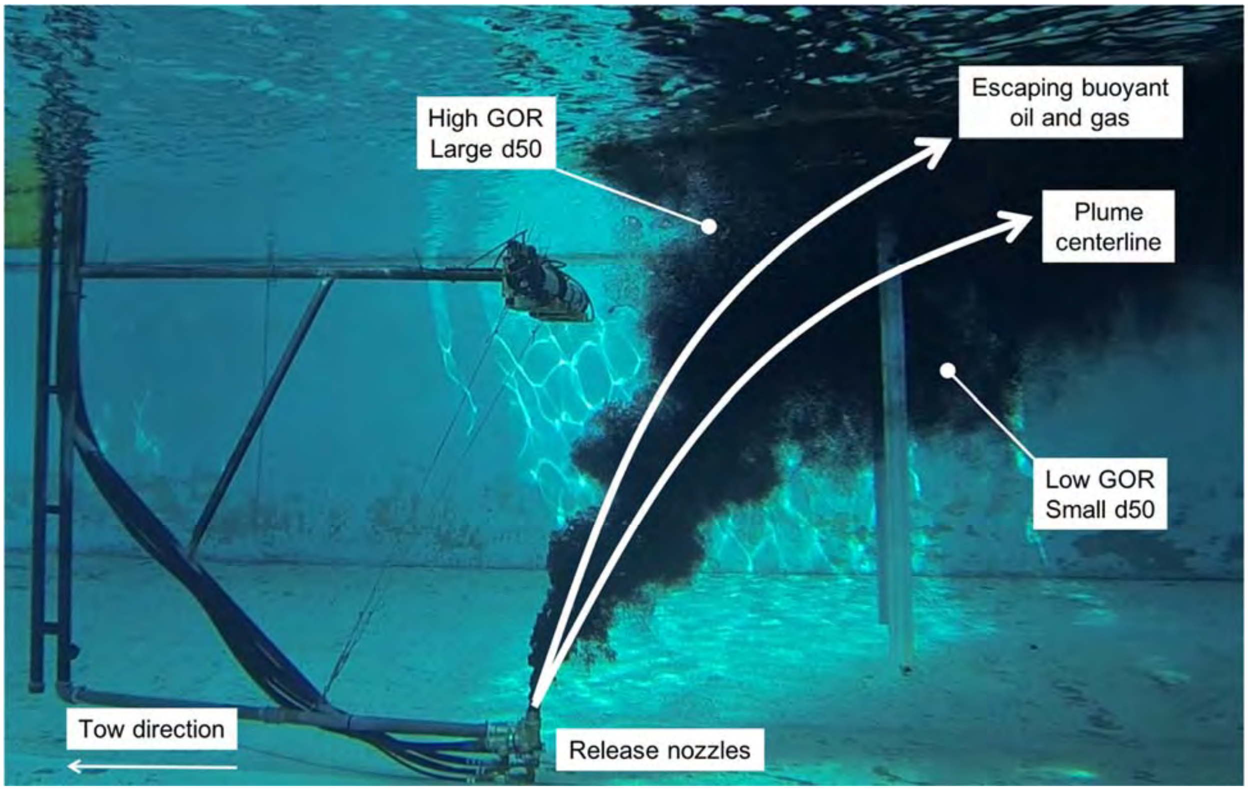

Figure 24. Schematic illustration of gas and size fractionation during a towed release.

The accuracy of the oil and gas differentiation appears to be worse in situations with dispersant injection, including in scenarios with water, gas and dispersant which also causes a reduction in gas bubble size (Brandvik et al. 2016). The increased error in these cases is likely an artefact that results from the smaller particles present, which have fewer pixels available for identifying the differentiating features of oil and gas, and therefore a more challenging situation for the neural network. Therefore, the accuracy of the GOR estimate will be worsened for smaller sizes. As the dispersant is a clear liquid, it is unlikely for the dispersant itself to the source of this error. If very small droplets are of interest, a higher resolution SilCam should be used, as is presented by and Brandvik et al. 2016 and Davies et al. 2017. However, such small droplets are unlikely to be relevant for a full-scale blowout scenario (Johansen et al. 2013).

So far, the SilCam has been used on light crude oils and varying dispersant types, and also live oil (Brandvik et al. 2016). It is likely that oil type has little impact on the method presented in this paper, although possible re-training of the neural network could be necessary if new types of oil have significantly different optical characteristics. Condensates, for example, could prove problematic due to their high transparency making them appear similar to gas bubbles.

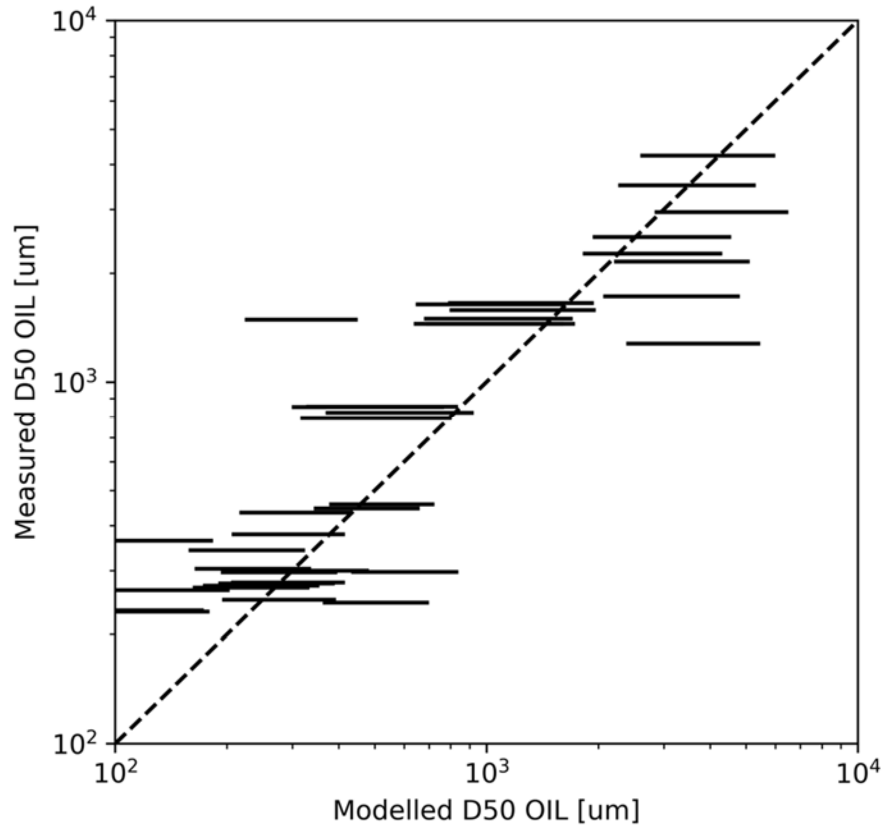

Figure 25. Comparison of modelled oil droplet d50 (x-axis) and measured d50 (y-axis). The modelled oil droplet size is calculated using a +/-10% tolerance on the input data (nozzle diameter, release rate, GOR and IFT) to reflect the variability and uncertainty in the experimental conditions. Thus, the modelled d50 values are presented as lines which span the minimum to maximum range of sizes based on the 10% tolerance.

In addition to predicting the d50 of oil – where the Modified Weber model appears as an accurate estimator – it is of interest to examine the predictability of the gas bubble size in such large-scale situations. This is not a parameter that is modelled directly using the approach of Johansen, Brandvik and Farooq, 2013, but it is possible to relate the predicted oil droplet size to the measured gas bubble size. The effect of extra 'crushing' of oil droplets can be approximated in the model by increasing the release rate to match the total rate of oil and gas. After this corrected oil droplet d50 has been calculated, the gas bubble size appears to follow approximately 1.5x that of the oil droplet size. This factor was approximated by examination of small-scale releases of mixed oil and gas, collected previously for vertical releases. The experiments conducted at OHMSET in 2018, as part of this project, support this method of estimating a gas bubble size, although a multiplier of 1.36 instead of 1.5 was found to correlate best with these large-scale tests (Figure 26) – albeit with the caveat that many of these tests are subject to greater uncertainty due to the fractionation occurring from the tilted plumes. In addition, it is worth noting that oil-coated gas bubbles will likely follow a different scaling relationship to oil droplet size than the pure gas bubbles, and thus oil-coated gas bubbles (treated as gas bubbles here) will introduce additional scatter when compared to the oil droplet size.

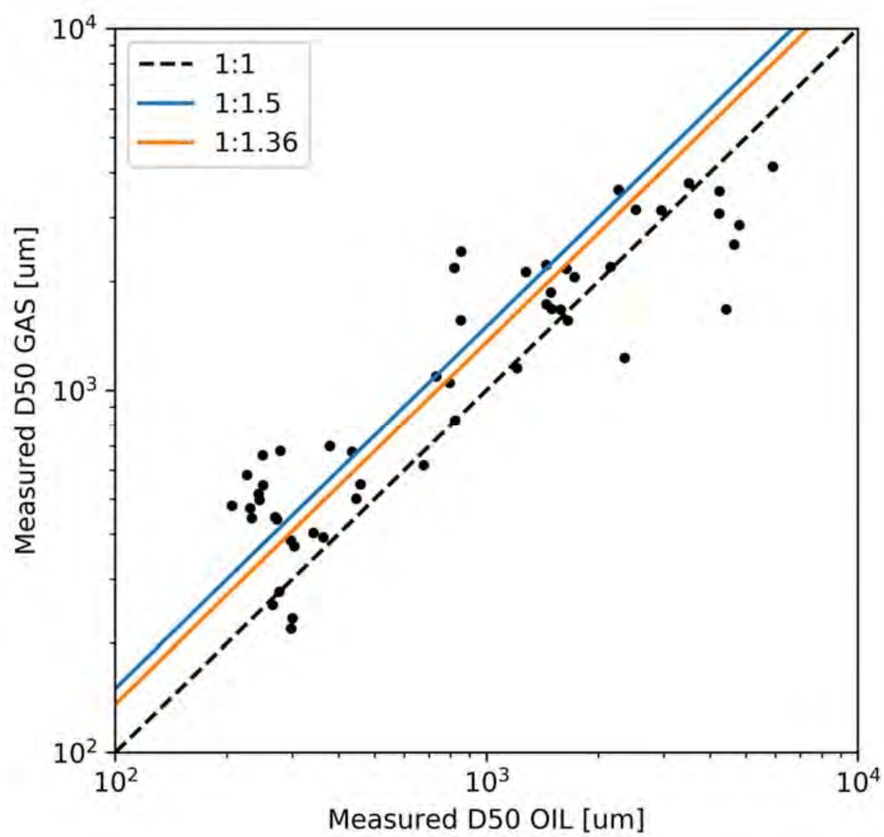

Figure 26. Comparison of measured oil droplet d50 and gas bubble d50. The black dots show average d50s for each experimental release, the dashed black line shows a 1:1 fit, the blue line shows the expected 1.5x relation that was approximated from small-scale tested conducted by the API D3 dispersant injection research, and the red line shows the best fit from the OHMSETT tests presented here.

6 Conclusions and Recommendations

6.1 Oil Droplet and Gas Bubble Measurements

Large-scale experiments show that reductions in droplet size of an order of magnitude are possible with effective dispersant application (for example a median droplet size reduction from 3.0 mm or 3,000 µm to 300 µm) and align with other recent blowout research (Brandvik et al. 2013, 2016; Johansen et al. 2013).

While complications due to the shallow depth of the OHMSETT tank make testing difficult, results from the extensive monitoring demonstration tests presented here show blowout plume monitoring can now be conducted by mounting a SilCam on an ROV and placing the SilCam in the rising oil and gas plume above the discharge. The results presented give confidence that, in a real blowout situation, the SilCam can provide a measure of oil droplet and gas bubble size distributions by a SilCam operator working closely with the ROV operator to ensure the SilCam is best placed to make measurements.

Droplet/gas bubble measurements should to be collected with and without dispersant application to determine the effect of the dispersant. These oil droplet and gas droplet size data can be used for several purposes:

- Verifying subsea dispersant is reducing oil droplet size
- Modelling oil spill trajectory input
- Optimizing dispersant application
- Determining gas to oil ratio

Such data should significantly assist in the evaluation of subsea dispersant efficacy and aid in spill response decision making.

6.2 SilCam Technology Readiness Level

BSEE sponsored a project in 2015 to develop the TRLs for Oil Spill Response Technologies and Equipment which enable the oil spill response community to objectively classify the various oil spill response tools and technologies under development. This was achieved through a series of meetings and discussions involving a broad spectrum of the oil spill response community including government agencies, nongovernmental organizations, non-profit organizations, technology providers, large oil exploration and production corporations, oil spill response organizations, and those who operate oil spill testing facilities. The group worked to come to agreement on 9 TRLs, ranging from TRL 1 where basic research begins to transition to applied research, and culminating in TRL 9 where the technology is deployed to mitigate an oil spill in a real spill environment. The 9 TRLs are described in BSEE report OSR-1042AA, TRL Definitions for Oil Spill Response Technologies and Equipment.

Our objective in this project was to bring SilCam monitoring technology up to TRL 8. An excerpt from the BSEE TRL definitions for level 8 is shown below:

TRL	Brief Description	Detailed Description
8	Final integrated system tested in real or relevant environment	The final integrated system has been proven to function in real or relevant environment with performance and operational specifications and limitations defined. Reproducible data to support claims has been documented in publicly available publications. The technology is ready for spills of opportunity and field use.

From Table 7. TRL 8 description from BSEE Oil Spill Response Technology Readiness Levels of BSEE report OSR-1042AA, TRL Definitions for Oil Spill Response Technologies and Equipment

Using the description above and given the demonstration of the SilCam prototype, training and documentation available described in this report, the SilCam is now at TRL 8 as defined in BSEE report OSR-1042AA. BSEE has accepted a prototype ready for subsea use up to 3,000m depth and ready for mounting on a suitable ROV. Training and monitoring guidance has also been provided to BSEE and OHMSETT personnel. In the event of deep-water blowout, the SilCam prototype is ready for deployment in a real spill environment.

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Appendix A

SilCam Operating Manual

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SINTEF Ocean, Department of Environmental Technology

SilCam User Manual

2018 Version for Experimental and ROV Mounted Monitoring

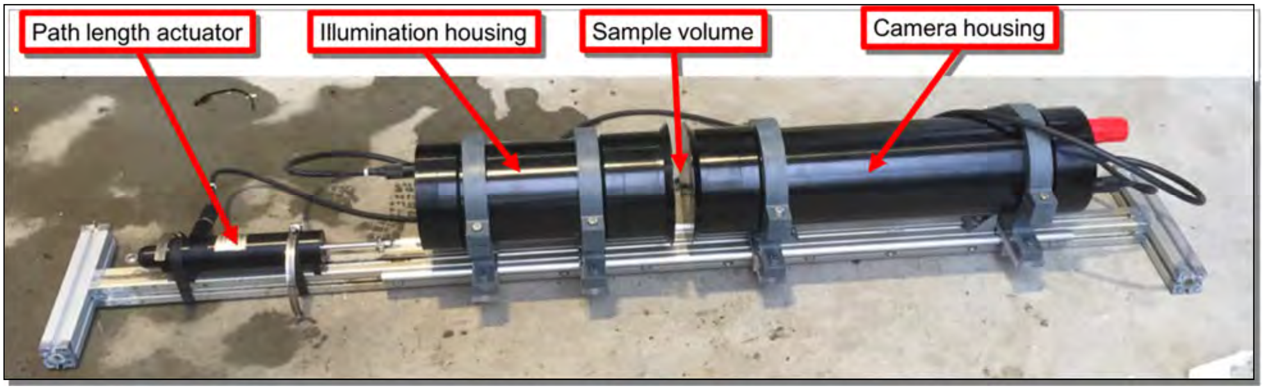
This is a manual for basic setup and use of the SilCam Blowout Monitoring Instrument. This is not a technical manual that details how to assemble or change the configuration of the system.

Version Date: 30th May 2018

Contents

Hardware

Overview



The system is shown in the photo above. It consists of three housings: 1) subsea linear actuator for adjusting the length of the sample volume; 2) illumination housing; 3) camera housing. These housings are mounted in-line on a single bracket. Additionally, an in-situ cleaning system is mounted on the same bracket, directing cleaning nozzles towards the windows of the illumination and camera housings. When deployed, this should be mounted upside-down than as in the figure, such that the rising droplets enter the sample volume without disruption from the mounting bracket.

Cables and connections

There are two black cables: one connecting the path length actuator to the camera housing, and one connecting the illumination housing to the camera housing. There is also one 'primary' cable (coloured green) which connects to the 13pin circular on the camera housing and provides power and data to the system. For ROV integration, the female-female version of this primary cable can be used to interface to the ROV. For laboratory work, there is a different green cable with one 'dry' end for connecting to a power supply and laptop.

Before submersing the instrument make sure the illumination (black) and camera (green) cables are properly connected. The plastic collars around the cable Connector should be finger-tight. The bulkhead connector itself should not rotate relative to the housing. Rotation of these bulkhead connectors will mean that the housing will leak.

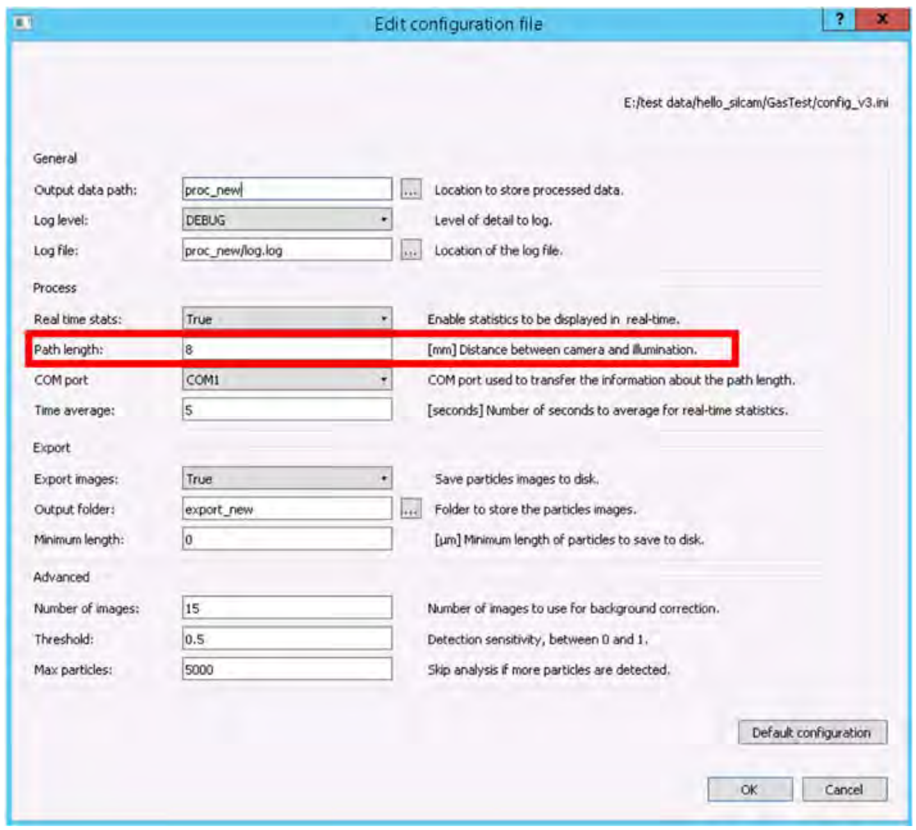
The connector pins for the cables should be handled with care so that they are not bent or damaged. Silicon spray / slider grease should be used to avoid damage (as is usual for submersible connectors such as this).

The SubConn Power Ethernet Circular (13 contacts) bulkhead standard is used. Information is available from MacArtney, here.

Pin	Colour on bulkhead connector	Function	Description
1	Black	24V GND	GND for camera, LED, path length actuator and RS232
2	Orange	NC	not used
3	White	Tx	RS232 Tx for path length actuator communication
4-11	--	Ethernet	Gigabit ethernet for camera data and communication
12	Red	24V+	Power for camera, LED and path length actuator
13	Green	Rx	RS232 Rx for path length actuator communication

Path length actuator

Adjusting the path length of the instrument should be done by setting the 'Path length' parameter in the config.ini file (see here for how to do this). When acquisition is stated, the instrument will then adjust itself to the path length specified. The path length to be used should be set so that there are minimal overlapping particles within the volume, but also so that the largest particles remain as undisturbed as possible. The optimal path length is a function of both particle size and particle concentration so may need adjusting mid-deployment. In this case, you should stop the instrument, edit the 'Path length' parameter in the config.ini file and restart the instrument. If you are saving raw data, it is recommended to also move to a new folder at this stage, as it will help with post-processing later.



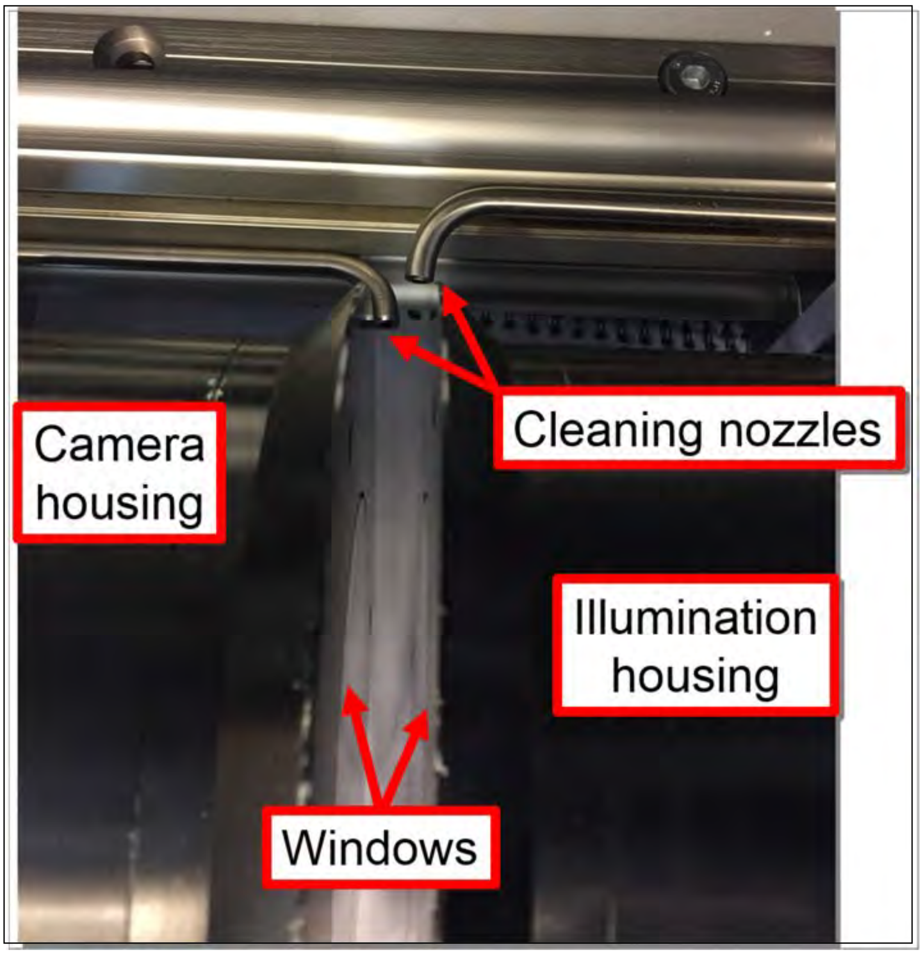
Calibration of path length

This is the only aspect of the SilCam which requires calibration. The easiest way to set the path length correctly, is by physically moving the attachment point of the actuator after starting the instrument with a given path length (as described above) For example, if you set the path length to 10mm and start the instrument, the housings will then adjust to a new position - you can then tune this position by moving the actuator housing along the attachment rail until the separation between the windows matched the set value in the config file. This separation can be measured with callipers to ensure accuracy.

The technical manual for the actuator unit is here

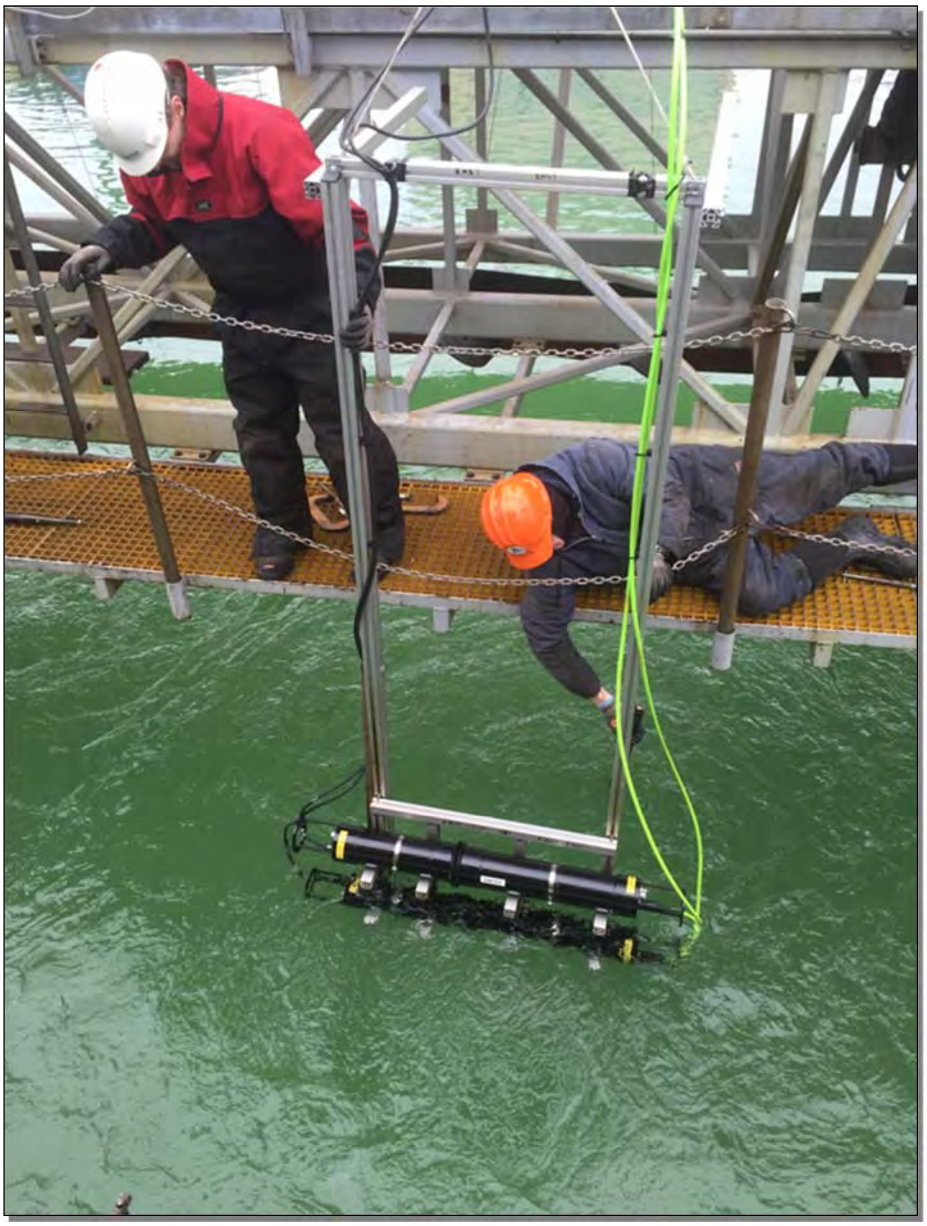
In-Situ Cleaning System

The cleaning system should be connected to a pump to provide water on demand at approximately 7 bar positive pressure. This is used for cleaning the optical windows when fouling becomes problematic. A photograph of the nozzles positioned above the sample volume is shown below.



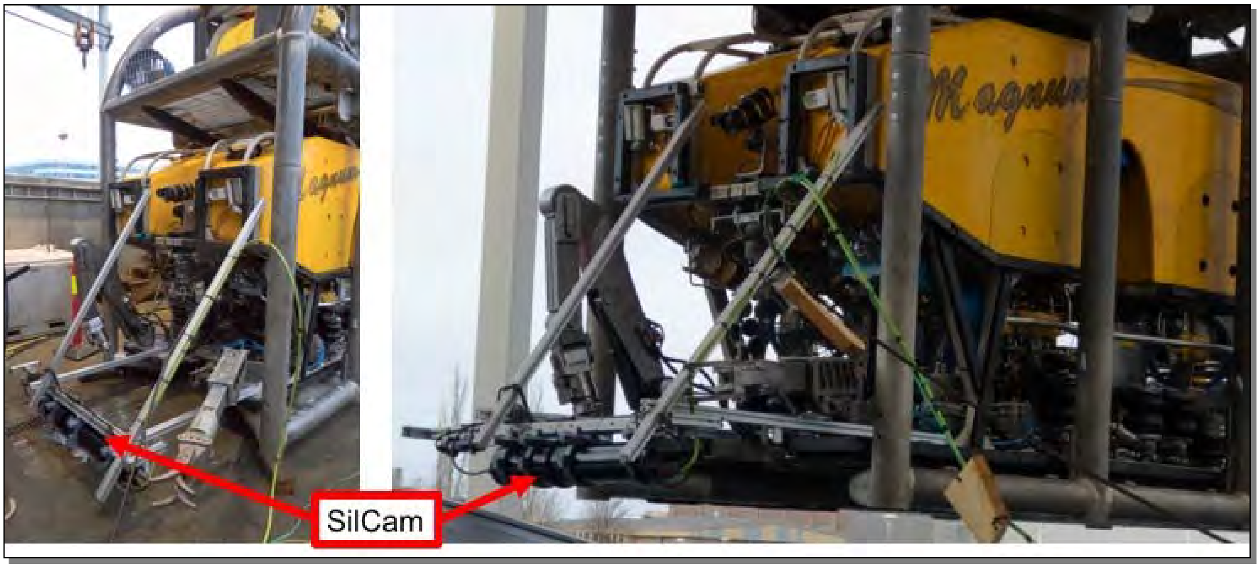
Laboratory Mounting

Mounting of the instrument for Laboratory use is relatively easy. The primary consideration is that the instrument should be mounted so that the primary flow direction of particles entering the sample volume is as undisturbed as possible. For example, during the 2015 Experiments at OHMSETT, the instruments were mounted horizontally so that plumes under the influence of relative cross-flow entered the sample volume from the side. A photograph of this setup is shown below, where two SilCam systems are mounted at different depths:



ROV Mounting

The system can be mounted in several different ways on an ROV. The photos below show a recommended mounting position in front of an ROV, such that the instrument can be inserted into a plume without having to fly the ROV itself into the plume.



Power

Power needed is 24V DC and may require a maximum of 2A. Peak current draw occurs for a short period (a few seconds) after the system receives power - this peak should be approximately 0.65A. During acquisition the system will draw approximately 0.5A. If the system is on but not acquiring, it will draw just below 0.2A.

A suitable power supply for the laboratory cable is included.

Data

Image data is transferred via Gigabit Ethernet (CAT 5e required) and is connected directly to the controlling laptop network adapter.

The path length is adjusted using RS232 serial communication and is connected to the controlling laptop via a USB-RS232 converter.

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SINTEF Ocean, Department of Environmental Technology

Deployment and Acquisition

Pre-deployment checks

Make sure the windows are clean. It is OK for the windows to have small smudges or specs of dirt because they will be removed during processing. However, it is important that there are not areas of the image which are completely black or completely white.

Warm, soapy water and a cloth should be sufficient for cleaning the windows.

Check that all cables are connected securely before powering on the instrument.

Example acquisition &/ processing workflow

Most interaction with the SilCam will follow the same workflow, whether performing basic system checks, analysing in real-time or post-processing historical data. This basic workflow is shown below.

Basic system check

Shortly after powering on the instrument, a network should become established between the laptop and the SilCam.

Load the SilCamGUI by double-clicking the desktop icon.

The GUI has three modes of operation for interacting with the instrument or data and are selected within the 'Acquisition control' window. These are:

1. Acquire images
2. Process historical data
3. Realtime processing

First, we will use the Aquire Images mode to check that the images from the system are acquired and that the windows are clean. Follow these steps:

1. Select "Acquire images"
2. Push the "Load config file" button and select a config file to load.
3. Push "Start"
4. Push "Live raw"
5. After a few seconds you should see images appear in the right-hand side of the main window of the GUI. No processing will be performed, so the graph will be empty and the smaller image on the bottom left will match the raw image on the right.
6. Check that the images are exposed well - they should have an even image intensity throughout the image, and there should be no areas of complete blackness or white.
7. Push "stop" when you are satisfied

Note: The refresh rate of this the main GUI window display when "Live raw" is active is purposefully slow and has a few seconds delay. You will therefore see snapshots of images every two seconds, even if several images are acquired or processed in-between. This is to ensure that computer resources for acquisition and processing are given the highest priority.

Acquire raw images without processing

A slightly higher sampling frequency is possible if you opt to process the data after acquisition. This can be useful in a laboratory experiment which is short in duration or in situations with rapid temporal changes. To simply acquire images to disc, follow these steps:

1. Select "Acquire images"
2. Push the "Load config file" button and select a config file to load.
3. Push the "Browse" button and navigate to a folder where you would like to store the data. It is highly recommended to navigate to a new folder each time you start acquisition, to help with data organisation. This is especially helpful when processing if you have altered the configuration file between stopping and starting.
4. Select the "Store to disk" checkbox and ensure that it is ticked.
5. Push "Start"
6. Push "Live raw" if you wish to see images.

    After a few seconds you should see images appear in the right-hand side of the main window of the GUI. No processing will be performed, so the graph will be empty and the smaller image on the bottom left will match the raw image on the right.

7. Push "stop" when you are satisfied.

Disk space: If acquiring images for long durations (more than 10 minutes), the hard drive of the laptop will fill up. If the hard drive becomes full, acquisition will continue to write empty files to disk, but these will not contain any data. It is therefore important to monitor that there is sufficient disk space when writing raw data. It is possible to acquire directly to a fast (USB3) external hard drive, which may be several TB in capacity. Alternatively, for very long duration acquisition, it is possible to use real-time processing without storing the raw data - this method will use significantly less disk space but lacks the option for re-processing at a later date.

Acquire images and process in real-time

Acquisition and real-time processing is possible with or without the option to save the raw data. Realtime processing without storing the raw data has the advantage of using significantly less disk space but lacks the option for re-processing at a later date. You should therefore be satisfied that the analysis settings in the config file are good enough for the situation if you opt to not save the raw data.

There are some elements of the configuration file which should be set for successful real-time analysis. Follow these steps to ensure that the configuration is appropriate:

1. Push the "Load config file" button and select a config file to load. You may wish to copy an existing config file and rename it for real-time analysis use.
2. In the main GUI window, select the "Tools" menu and go to "Edit config file".
3. In the "Process" section, make sure that the "Real time stats" is set to "True".
4. You may wish to edit the "Time average" value here too - this sets the duration (in seconds) over which to average the statistics when plotting the in the GUI window. This setting will not affect the processing, only the data displayed in the GUI.
5. Push "OK"

To acquire images and process in real-time, follow these steps:

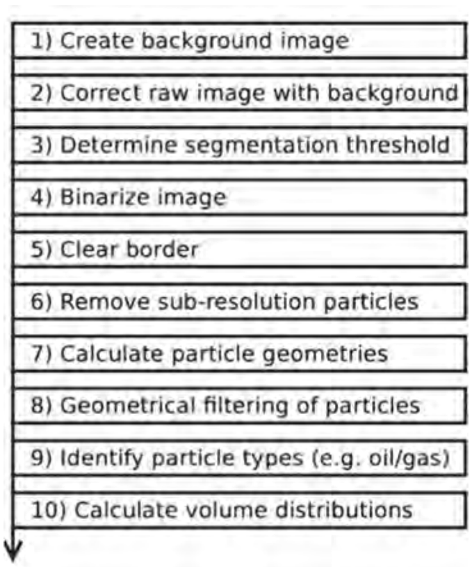
1. Select "Realtime processing"
2. Push the "Load config file" button and select a config file which is made for real-time analysis (see above points on setting up this config file).
3. Push the "Browse" button and navigate to a folder where you would like to store the data. It is highly recommended to navigate to a new folder each time you start acquisition, to help with data organisation. This is especially helpful when processing if you have altered the configuration file between stopping and starting.
4. Select the "Store to disk" checkbox if you would like to store the raw data in addition to the processed data.
5. Push "Start"
6. Push "Live raw" if you wish to see images and statistics.
    1. After a few seconds you should see images appear in the right-hand side of the main window of the GUI. The graph will display data and statistics as new images are processed, the smaller image on the bottom left will show the raw image, and the corrected image will be shown in the larger frame on the right.
7. Push "stop" when you are satisfied

Data processing and analysis

Overview

Data are analysed using the workflow published by Davies et al., 2017. The version of the software here is updated so that the differentiation (step 9 in the below figure) of oil and gas is now performed using a deep convolutional neural network. This is a method that relies on a database of 'know' particles types, which is used to train the network. Thus, the accuracy of the differentiation is dependent on the training set used. This method is faster and more flexible than that published by Davies et al., 2017 and maintains a high accuracy. It also enables removal of non-oil or gas particles (the Davies et al., 2017 method assumed than only oil or gas are present within the same volume, which could be problematic in a real spill with other material in the water column such as suspended sediments).

An outline of the analysis workflow is shown below:



For calculating properties of oil and gas, particles with a sphericity less than 0.9 are removed to avoid miss-calculation of overlapping particles, and particles with a deformation less than 0.3 are removed because oil and gas will split if deformed more than this.

Users do not need to understand the full details of all aspects of this analysis in order to use the system, as it is performed automatically and easily controlled using the SilCam GUI. However, if further details are desired, they can be found in the paper referenced below.

E.J. Davies, P.J. Brandvik, F. Leirvik, R. Nepstad, The use of wide-band transmittance imaging to size and classify suspended particulate matter in seawater, In Marine Pollution Bulletin, Volume 115, Issues 1–2, 2017, Pages 105-114, ISSN 0025-326X, https://doi.org/10.1016/j.marpolbul.2016.11.063.

Process historical data

If you have acquired raw images it is possible to process them by following these steps:

1. Select "Process historical data".
2. Push the "Browse" button and navigate to a folder containing raw data.
    1. A config file may already exist in this folder if the data were obtained using the standard acquisition workflow. In this case you will be prompted to load the auto-generated configuration file. If you do not receive this prompt, you should load a config file that is correct for the settings used in the acquisition for this specific dataset.
3. Push "Start" to analyse the data. This can take some time.

Exporting processed data

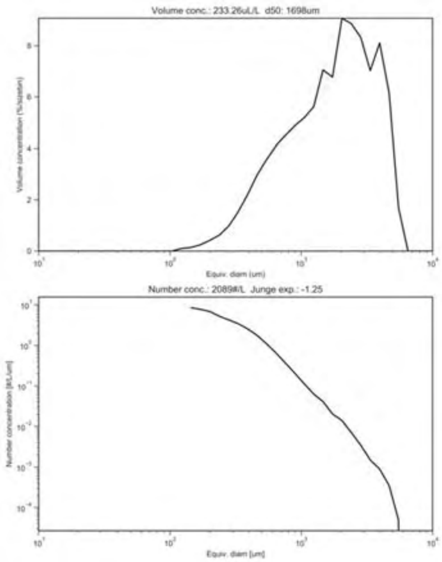
The location and name of the folder containing processed data can be altered in the config file by changing the "Output data path" field. While learning the system, it is recommended to use the default location which is called: "proc" and is a subfolder within the dataset location. Within this folder will be a file ending with "-STATS.csv". This is a large comma separated file containing statistics for every particle measured - it could be loaded and analysed in MATLAB, Python, or perhaps Excel etc. However, there is a lot of information in this file, which is often not necessary for size distribution analysis. To condense -STATS.csv files into a more useable format for size distributions, follow these steps:

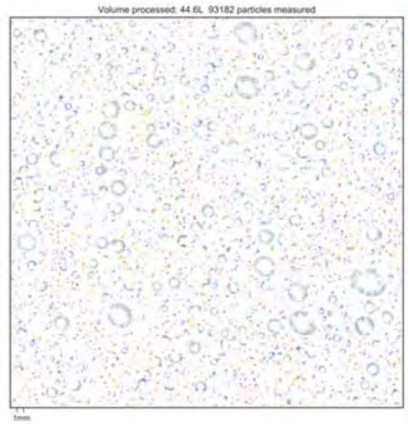
1. In the main GUI window, select the "Tools" menu and go to >Export >Summary time series (to xls)".
2. If you have not yet loaded a config file, you will be prompted to load one - this should be the same config file used in the processing that created the -STATS.csv file you wish to export.
3. You will then be prompted to select the -STATS.csv file you wish to export.
4. A series of new csv files will be created, which contain time-series size distributions of oil and gas, in a similar format to that produced by the LISST-100. This can be more easily handled in Excel, MATLAB, Python, or other analysis tools. In addition a *-d50_TimeSeries.png file will be created, showing the time-series of d50 of oil and gas and the GOR.

Note: d50 is a measure of median particle size. It has no relationship to concentration. Therefore, it is subject to spikes when concentrations are low. For example, in situations such as a GOR of zero, a few miss-classified gas BUBBLES may appear significant in a plot of d50, even though this may contribute a small error in the volume concentration.

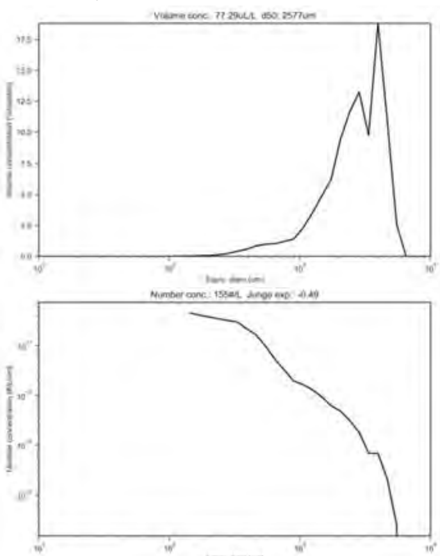
If you do not wish to make plots yourself, you can follow the above steps, but select >Export >Summary figure (to png) instead, and the software will create summary size distributions and statistics for the dataset. An example of a summary of figures generated from a mixed oil and gas release, is shown below - three figures will be generated: one for all particles, one of just gas and one for just oil:

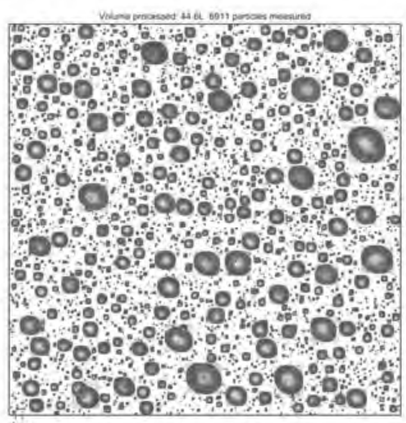
Summary - all



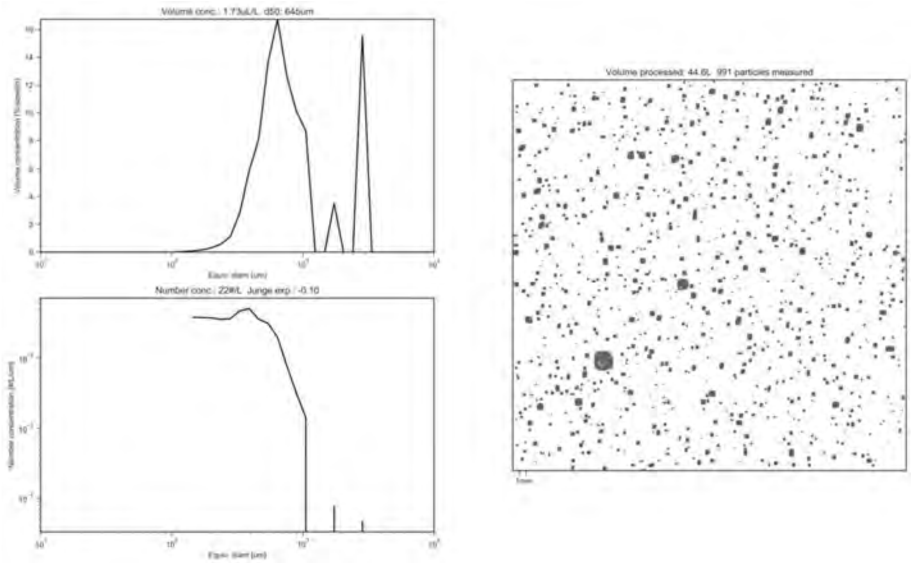


Summary -Gas



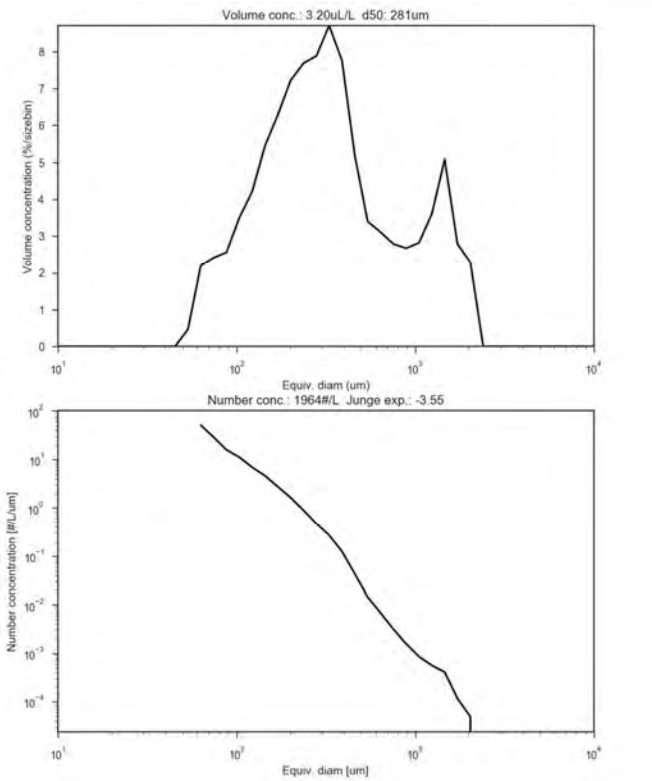


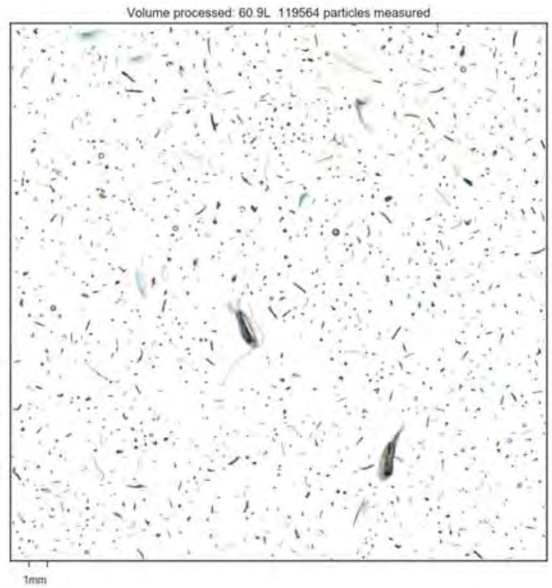
Summary - Oil



The statistics here are averages for the dataset selected. The top left plot shows the volume distribution, with text information on the average volume concentration and d50. The bottom left plot shows the number distribution, with text information on the average number concentration and the Junge slope (the Junge slope is used to indicate the relative proportion or large and small particles in Ocean waters assuming a negative power-law number distribution; this statistic is not so relevant for oil and gas plumes). The right-hand image is an auto-generate montage of randomly-selected particles recorded; this is used as a general overview of what the sample 'looks like' and is intended to conform approximately to the measured size distribution, but not to the measured concentration. The text above the montage shows the total volume of water analysed and the total number of particles measured.

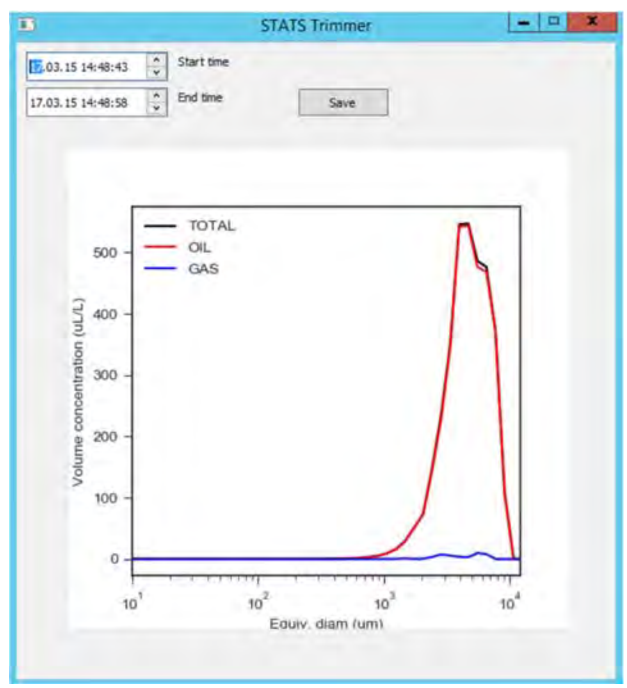
Note that the montage in summary figure for 'all' particles will look different from the oil and gas montages. This is because a different method of image enhancement is used for the montage of 'all' particles, which is better at resolving features in zooplankton and marine snow but performs poorly on low-contrast particles such as oil and gas. Thus, the two separate summary figures for oil and gas contain montages that are clearer. An example of a summary figure for 'all' particles obtain in a natural ocean environment is shown below:





Exporting subsets of long time series

For large datasets, the processed STATS.csv files can take time to load and contain a lot of information that is not always needed. For example, if you just want to look at size distributions from a selected time window. Use the Trim Stats tool under: “>Tools >Export > Trim STATS file” to select portions of a time series and save the output as a new STATS file for easier handling. The produced file will have the start and end times of the selected segment written into the filename, so the original STATS file will not be overwritten. You can then refer to this new STATS file for subsequent plotting and exporting of the time segment of interest (as explained in the above sections).



Viewing raw data

The raw images are stored as time-stamped binary arrays with a ".silc" file extension. It is therefore important never to rename these files because the filenames contain the information about when the images were obtained, which is used when processing. Unfortunately, it is not possible to browse through .silc file thumbnails as it is with other image formats such as bmp. There are two options in the "Tools" menu to help with viewing raw data:

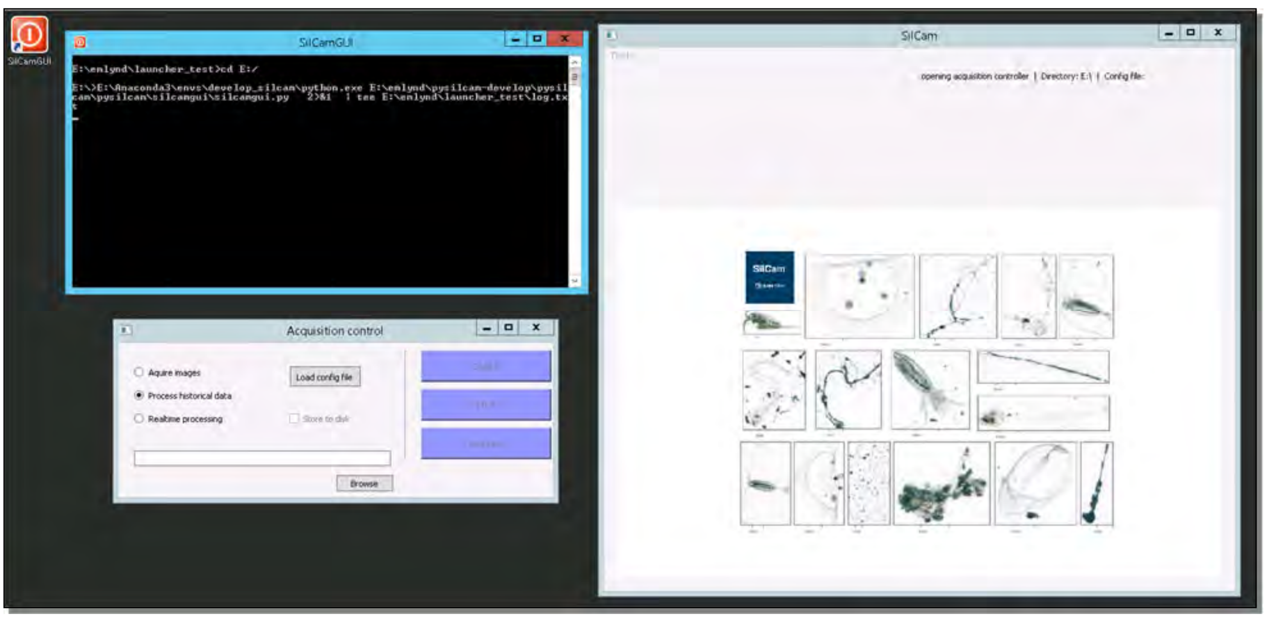
1. use the "silc file player". This is essentially a traditional video player with pause, forward and rewind options. This can be useful for quick inspection of the beginning of a dataset but is a time-consuming for larger time-series.
2. convert the silc files into bmp files, which can then be viewed as thumbnails, by using the "Convert silc to bmp" option.

Overview of SilCamGUI

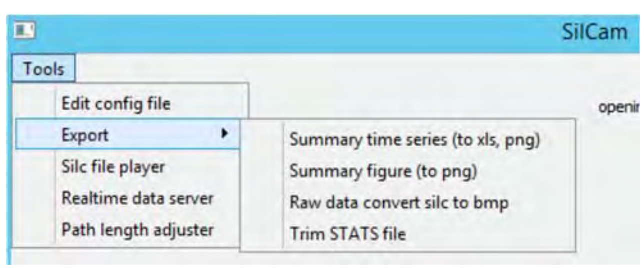
The GUI can be launched using the desktop icon.

There will appear three windows:

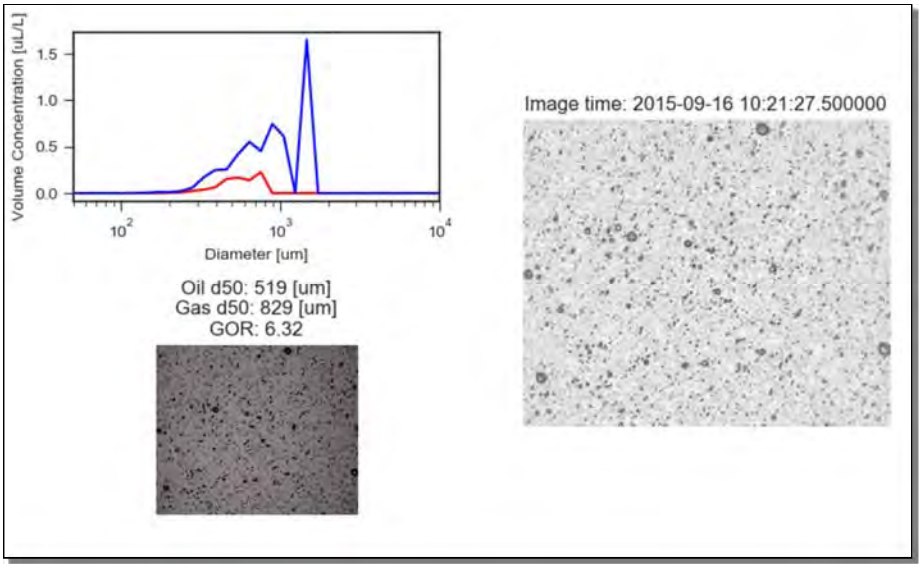
- A terminal window for displaying of detailed information on the 'backend' processes. There is no need to interact within this window, but it should remain open. Do not close this window. If you experience errors while running the software, you should copy the text in this window and save it to a text file. This information can then be used to help identify and fix the problem.
- An 'Acquisition control' window for interacting with the camera and controlling data processing. It is not possible to close this window.
- A main 'SilCam' window, which is primarily for displaying data and figures during acquisition or real-time processing. Updates to plots presented in this window are activated by using the 'Live raw' button in the 'Acquisition control' window. There is also a 'Tools' menu within this window, which can be used for post-analysis, exporting and plotting. Closing this window will terminate the software.



The tools menu is found in the top left of the main SilCam window, and is where you can find options for editing the config.ini file and also plotting and post-processing tools:



An example of statistics plotted when the 'Live raw' button is activated are shown below. This example is of a gas release, without oil.



The top left plot shows the particle size distribution of gas in blue, and oil in red. The d50 of oil and gas and the GOR, is also printed in text underneath this plot. The statistics shown here are averaged over the period specified by the 'Time average' within the config.ini file. It is usually recommended to use a minimum of 30 seconds for this 'Time average' value.

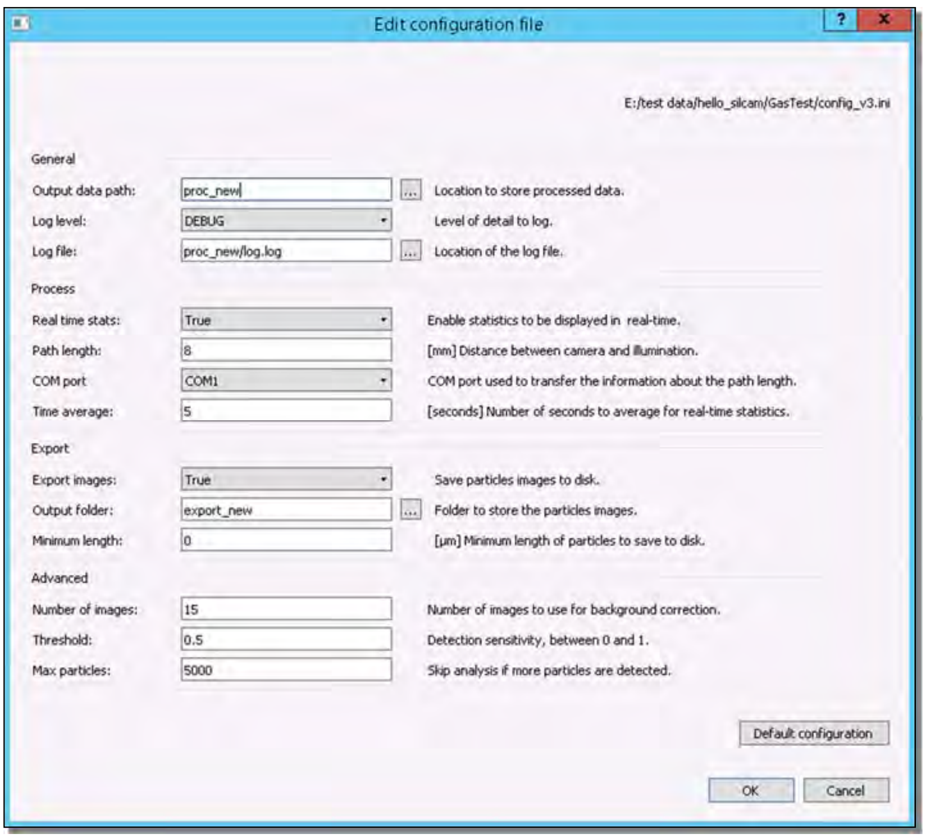
The bottom left image shows a raw image (uncorrected). The right image shows the corrected image following background correction.

The 'Live raw' mode will only refresh the figures every 1-2seconds, even if there is backend processing running at a faster rate. This is mainly to prioritize computational resources for processing, and also to help users see the figures without them refreshing too fast.

The config.ini file

This is the most important file for the software because it specifies everything from how the images should be acquired to how the output data should be saved. Thus, a config file must be loaded before doing most tasks within the SilCamGUI. You can load a config file by clocking 'Load config file' in the 'Acquisition control' window.

There are many parameters in here which should not need changing if the instrument is to be used repeatedly for similar applications. However, it can be sensible to save different config files if you find that some datasets require different configurations. The most commonly adjusted settings can be edited with a helper window from within the SilCamGUI. To edit basic elements of a config.ini file, go to the 'Tools' menu in the main 'SilCam' window, and select 'Edit config file'. This will launch the window shown below, which provides information on the parameter which you are free to edit:



There are more advanced parameters within the config.ini file that are not editable from the SilCamGUI. To edit these, you must open the config.ini file using a text editor such as WordPad, and modification of these other settings should be only done under consultation with SINTEF Ocean (Emlyn.davies@sintef.no).

Instrument specific parameters

The unit is rated to 3000m depth.

The magnification is 0.125x, yielding a pixel size of 28.758 microns.

The camera has a resolution of 2048x2448 pixels and records 8bit RGB images which are approximately 15Mb each. The camera is an Allied Vision GC2450c. The technical manual can be accessed here.

Further reading, examples and presentations

"Combining optics, imaging and artificial intelligence for in-situ characterization of complex particle populations" AGU Ocean Sciences, Feb 2018

"Advancing technology for measuring particles": https://www.dropbox.com/s/uam39el73cyferf/SINTEFParticleMeasurementsJune2017.pptx?dl=0

SilCam methods paper: E.J. Davies, P.J. Brandvik, F. Leirvik, R. Nepstad, The use of wide-band transmittance imaging to size and classify suspended particulate matter in seawater, In Marine Pollution Bulletin, Volume 115, Issues 1–2, 2017, Pages 105-114, ISSN 0025-326X, https://doi.org/10.1016/j.marpolbul.2016.11.063.

Mine tailings measurements: Emlyn J. Davies, Raymond Nepstad, In situ characterization of complex suspended particulates surrounding an active submarine tailings placement site in a Norwegian fjord, In Regional Studies in Marine Science, Volume 16, 2017, Pages 198-207, ISSN 2352-4855, https://doi.org/10.1016/j.rsma.2017.09.008.

Summary of oil spill measurements: Brandvik PJ, Johansen Ø, Davies EJ, Leirvik F, Krause DF, Daling PS, Dunnebier D, Masutani S, Nagamine I, Storey C, Brady C. Subsea Dispersant Injection-Summary of Operationally Relevant Findings From a Multi-Year Industry Initiative. InSPE International Conference and Exhibition on Health, Safety, Security, Environment, and Social Responsibility 2016 Apr 11. Society of Petroleum Engineers. https://doi.org/10.2118/179401-MS

Particle tracking: E. J. Davies, P. J. Brandvik and F. Leirvik. The use of optics for inferring properties of subsurface oil and gas particles, AGU: Ocean Sciences Meeting, Honolulu https://www.eposters.net/pdfs/the-use-of-optics-for-inferring-properties-of-subsurface-oil-and-gas-particles.pdf

Appendix B

Silhouette Camera Subsea Dispersant Monitoring Plan

Exponent®

SINTEF

Silhouette Camera Subsea Dispersant Monitoring Plan

BSEE Contract E17PC00009

Silhouette Camera Subsea Dispersant Monitoring Plan

BSEE Contract E17PC00009

Prepared for

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September 14, 2018

1602129.000 – 3415

Contents

List of Figures

List of Acronyms and Abbreviations

API	American Petroleum Institute
bmp	Bitmap Image Format
BSEE	United States Bureau of Safety & Environmental Enforcement
d50	Median Droplet Diameter by Volume
DOI	Department of the Interior
DWH	Deepwater Horizon
EPA	United States Environmental Protection Agency
FOSC	Federal On-Scene Coordinator
GOR	Gas to Oil Ratio
GUI	Graphical User Interface
Hz	Hertz
HTTP	Hypertext Transfer (or Transport) Protocol
ICS	Incident Command System
LISST	Laser In-Situ Scattering and Transmissometry
M	Meters
µm	Micron
mm	Millimeters
NCP	National Contingency Plan
NRT	National Response Team
png	Portable Network Graphics Format
QA	Quality Assurance
QAPP	Quality Assurance Project Plan
ROV	Remotely Operated (Underwater) Vehicle
RP	responsible party
RRT	Regional Response Team
SilCam	Silhouette Camera
SINTEF	SINTEF Environmental Technology
SMU	Subsea Monitoring Unit
TR	Technical Report
UC	Unified Command
VOC	Volatile Organic Compound
Wi-Fi	Standardized Wireless Local Networking

Disclaimer

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This document is a general plan for use by the BSEE of a Silhouette Camera to monitor oil droplet and gas bubble size in the event of a subsea oil release. It is not a detailed plan which can be used in a specific event. Instead, a monitoring plan specific to any actual situation's circumstances should be developed and approved by the appropriate regulatory authorities.

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This monitoring method is intended for use by trained BSEE users who have an understanding of Silhouette Camera's design, operations and limitations. Interpretation of the data is intended to be done by BSEE scientists familiar with oil spill science, especially the use of dispersants subsea.

Abstract

This document is intended to supplement existing industry guidance such as the API subsea dispersant monitoring plan document (API TR 1152). Here, we describe a new method of monitoring subsea dispersant efficacy directly using the new technology, the Silhouette Camera (SilCam), which can directly measure oil and gas droplet size in the release plume near the point of subsea release. SilCam monitoring will allow direct subsea observation changes in the oil droplet size due to dispersant oil treatment and provide a method of ongoing assessment of subsea dispersant operations as well as provide opportunities to monitor gas subsea and to estimate the oil to gas ratio of the release. This new method can then be used instead of indirect methods of subsea dispersant efficacy such as aerial photography, near surface VOC monitoring or visual ROV camera observations.

1 Introduction

The purpose of monitoring as described in this document is to determine dispersant efficacy and characterize the nature and extent of subsea oil and gas plumes. Information generated by this monitoring will guide the development of, or modifications to, and operations of subsea dispersant application that inform decisions to continue, modify, or discontinue dispersant applications. Additional data about the subsea oil and gas discharge characteristics can also be collected using SilCam.

This document describes a proposed method for direct monitoring of a subsea oil plume and the efficacy and characteristics of subsea dispersant injection in the subsea plume to inform operational oil spill response decision-making and Unified Command (UC) strategies for protecting worker health and safety. Along with API TR 1152 (API 2013), it is intended to be used as a model which can be modified to meet the needs of a specific facility or incident.

This method is intended be part of the monitoring that complements the Subsea Dispersant Operations Plan in an oil spill response. This monitoring does not address surface dispersant operations or monitor for environmental effects. The dispersant efficacy monitoring plan proposed here is intended to be consistent with Subpart J of the National Contingency Plan (NCP) (40 CFR 300.910) and applicable National Response Team (NRT) and Regional Response Team (RRT) guidance, plans, or requirements.

During the Deepwater Horizon (DWH) oil spill of 2010, subsea dispersant injection was used as a response option in addition to other methods that have been more commonly applied during other events. At the time of the spill, there were no standardized methods for monitoring the efficacy and environmental effects of subsea dispersant use. During the DWH response effort, a unique organizational unit of the Incident Command System (ICS) structure, known as the Subsea Monitoring Unit (SMU), was created and monitoring methods were developed and modified as the event progressed. Those methods became the basis for policy and guidance development efforts within governmental agencies and industry. Three guidelines have been written to provide support to responders in the event of another unplanned subsea oil release.

The American Petroleum Institute (API) developed a “model plan” for all aspects of subsea dispersant monitoring that could be used by its member companies as the basis for facility response plans, or Incident Action Plans for a spill event, API Technical Report 1152, *Industry Recommended Subsea Dispersant Monitoring Plan*. This document describes a proposed method for monitoring the efficacy and character of subsea dispersant injection to inform operational oil spill response decision-making and UC strategies for protecting worker health and safety. It is intended to be used as a model which can be modified to meet the needs of a specific facility or incident. This plan is intended to complement the Subsea Dispersant Operations Plan, but does not address surface dispersant operations.

As a further aid to industry oil spill responders seeking approval for dispersant use, API also has written, *Industry Guidelines on Requesting Regulatory Concurrence for Subsea Dispersant Use*, API Bulletin 4719. Lastly, the United States Government National Response Team (NRT) created a guidance document that addresses “atypical” dispersant uses in general, *Environmental Monitoring for Atypical Dispersant Operations*. This NRT guidance is intended to be used by RRTs, but also contains specific guidelines for use by responsible parties (RPs).

2 General Purpose of Monitoring Subsea Dispersant Operations

Environmental and human health monitoring plans form an essential element of comprehensive and actionable oil spill preparedness and response plans. This document and API TR1152 recommend monitoring activities to support subsea dispersant injection operations. Subsea dispersant injection, to date, has only been associated with well blow-out releases. The approach involves adding dispersant, via a remotely controlled underwater vehicle or a fixed injection system associated with a capping stack, directly into the released oil flow in the immediate vicinity of the release point. The intent is to limit the formation of a surface oil slick, to minimize the aerial release of volatile compounds at the spill response site (a threat to worker health and safety), to prevent or reduce the potential for floating oil to impact sensitive environmental resources, and to enhance the potential for microbial biodegradation. It is important that monitoring be conducted in a manner that provides actionable data for decision-makers within the ICS.

SilCam monitoring data can be used to help decide whether to continue or modify subsea dispersant use. The data helps spill responders make more informed decisions about the way to use subsea dispersants in combination with other spill response technologies. A detailed monitoring plan helps identify the supplies, equipment, staff and activities needed to monitor subsea dispersant injection effectively in the event of a spill. Addressing these requirements beforehand through response planning helps produce more efficient and effective results during the response effort. This document contains a recommended approach to SilCam monitoring and includes a list of resource requirements for implementing an effective monitoring program. SilCam monitoring team members will consist of personnel specially trained not only for the technical operation of the equipment, but also interpretation of the data to support operational decisions.

The existing NRT Guidance for *Environmental Monitoring for Atypical Dispersant Operations*, and United States Environmental Protection Agency (EPA) Region VI currently require that monitoring assets be in place prior to dispersant injection. Federal On-Scene Coordinator (FOSC) approval should be sought for any required deviation from those policies.

3 Silhouette Camera Technology

Understanding the oil droplet sizes that exist under differing blowout or subsea release scenarios is fundamental to response decision making and assessing ecosystem impact. Existing, commercially available monitoring devices all have significant limitations (e.g., cannot differentiate between gas and oil or have limits in the range of droplet sizes that can be measured). This makes monitoring of a subsea blowout and subsequent dispersant application with these devices of limited practical use in understanding the nature of the release and impact of the response. SilCam extends subsea monitoring capabilities by adding an accurate, and direct monitoring method for the key parameters of oil droplet and gas bubble size in the subsea plume.

Beginning in 2013, SINTEF Environmental Technology (SINTEF) developed a novel in-situ particle imaging system (‘SilCam’) that has been used to quantify the size and concentration of material suspended in seawater. Examples include: gas bubbles, oil droplets, plankton, and suspended sediments. This imaging system has enabled the extension of particle measurements into larger size ranges and higher concentrations than were previously possible. Currently, SINTEF has produced multiple research versions of the system, including one with a modified housing design for use in depths of up to 3000m. Software for data analysis has been developed to support the SilCam hardware to provide real time data on droplet and bubble sizes along with a gas to oil ratio estimate. An outline of Silcam’s capabilities versus other optical instruments relevant for oil spill measurement is shown in Figure 1.

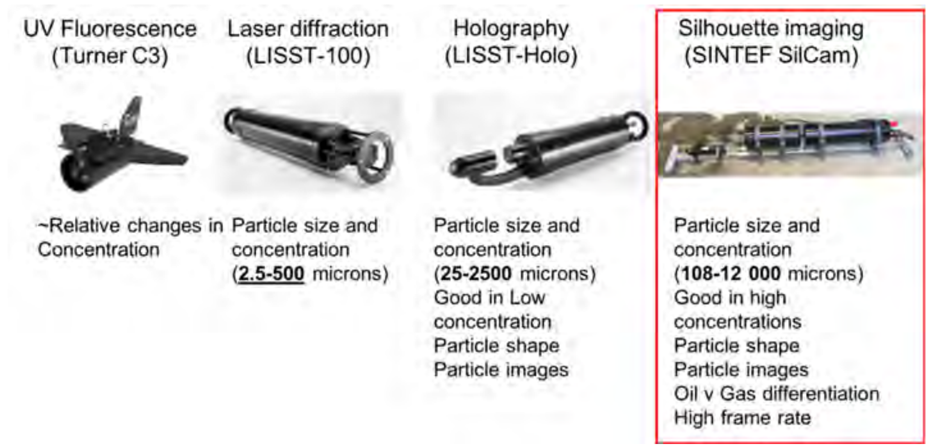

Figure 1. Overview of the range of commercially available optical instruments for oil droplet measurements, alongside the SilCam (indicated within the red box).

SilCam consists of a new particle imaging system designed to quantify high concentrations of suspended material within the ranges of ~108–12,000 µm. This system is specifically designed to combat challenges associated with standard imaging or video cameras through the use of carefully configured backlighting and telecentric-based receiving optics, creating an optical hardware configuration that ensures low-noise-level images where all particles in the sample volume are sharp, in focus, and free from the perspective errors associated with standard lens-based (or video) cameras. The large imaging volume (up to 65 x 55 x 40mm) and relatively high acquisition frequency (5Hz) of the SilCam enables reliable statistics of measured size distributions, as a 30-second averaging period could typically contain many hundreds-of-thousands of analyzed droplets from within a plume. In addition to the extension of the upper limit to measurable particle sizes, the system is able to characterize particle types based on individual optical properties of each particle. In this way, particles of equivalent geometry but differing composition can be separated and characterized. This is applied to quantifying independent size distributions and concentrations of oil droplets and gas bubbles within mixed releases, enabling the two populations to be analyzed independently and providing measurements of oil-gas ratios. A photograph of a SilCam (rated for 3000m depth) is shown in Figure 2, below:

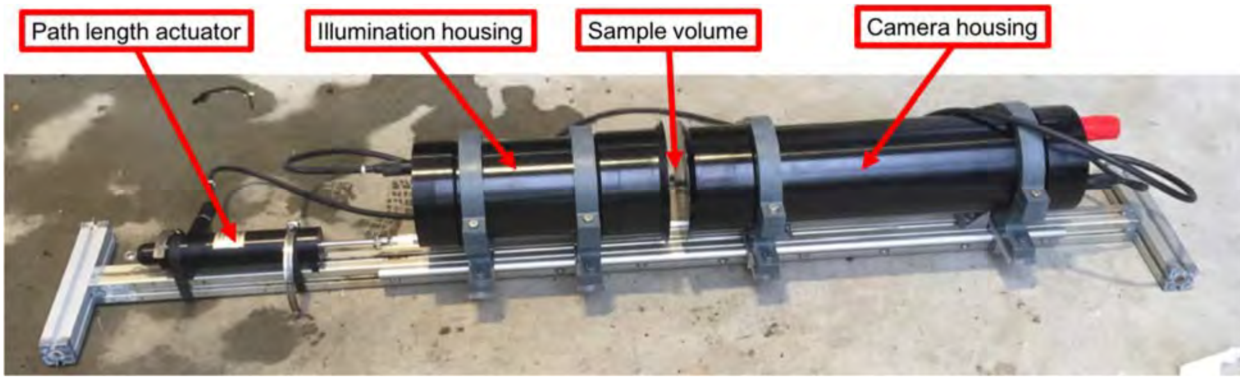

Figure 2. Annotated photograph of the SilCam system for in-plume characterization.

Images can be processed by real-time software to provide information on oil and gas median droplet size by volume (d50). Parallel processing is also implemented such that a modern multi-core laptop can process images faster by analyzing multiple images at once. Recent updates to the analysis method differentiate particles by using a convolutional neural network, implemented using Python and TensorFlow (by Google). The network has been trained on SilCam data of oil and gas, amongst other particles. As this training database grows, the number of identifiable particle categories can increase, and the accuracy of the classification will continuously improve.

Figure 3 shows a segmented image of identified oil and gas particles, which are subsequently used for calculating the population-independent geometrical statistics and size distributions.

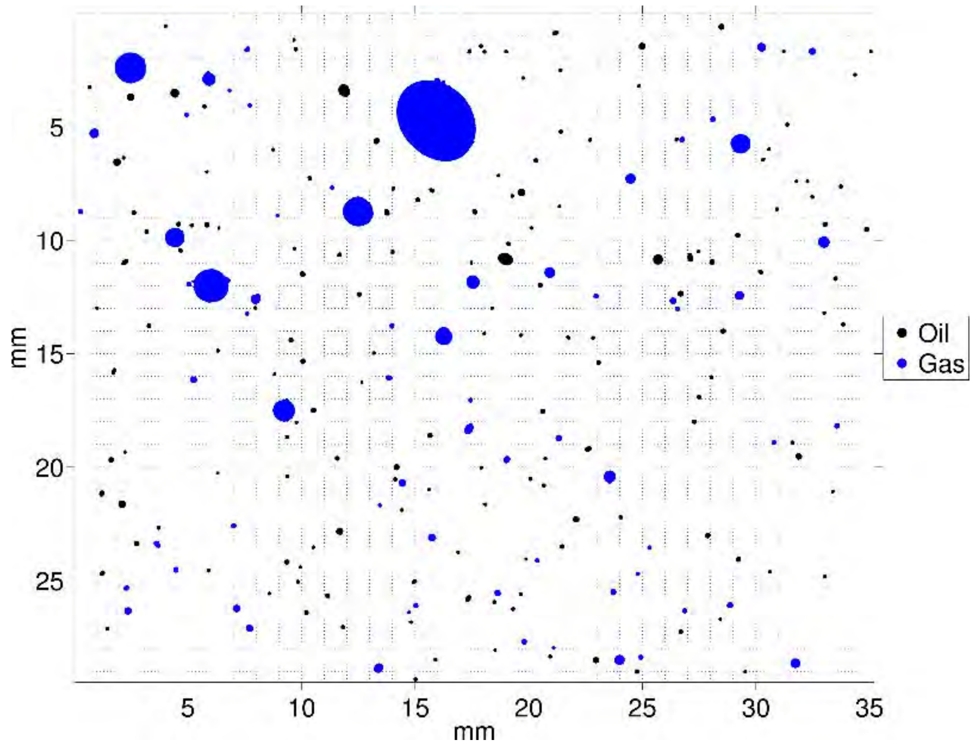

Figure 3. Example composite segmented image showing identified gas bubbles (blue) and oil droplets (black).

The SilCam software handles all aspects of data collection, processing and plotting, without the need for scripting or programming in order to operate the instrument. The graphical interface contains the following features:

- Acquisition of raw images from the SilCam (saving raw data is optional)
- Processing of raw data to size and classify particles
- Real-time processing of raw data (saving raw data is optional) that enables live plotting of oil and gas size distributions.
- HTTP serving of processed data, including a live stream of oil and gas d50, which can be accessed by other devices via Wi-Fi.
- Plot creations (summary figure of a dataset can be saved as a png file)
- Playback of raw data files
- Conversion of raw data files into bmp files
- Exporting of summary data to Excel

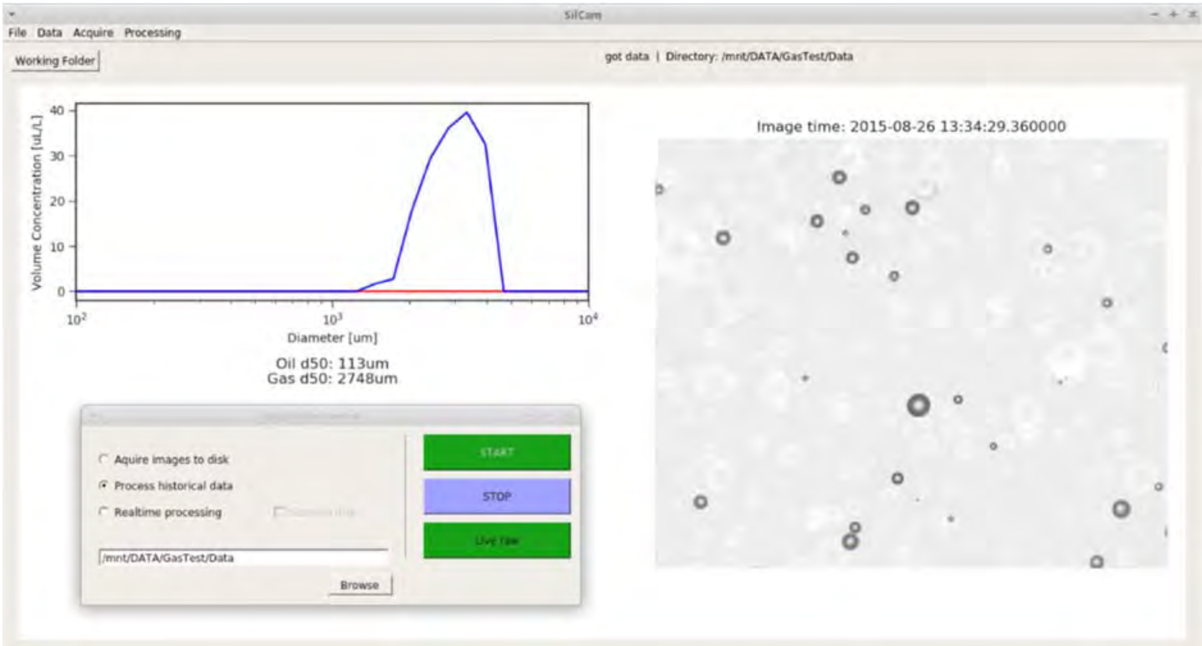

Figure 4. Screenshot of SilCam graphical user interface.

4 Subsea Droplet Formation and Median Droplet Size Prediction

4.1 The importance of oil droplet size in subsea releases

The size distribution of oil droplets formed in deep water oil and gas blowouts is known to have strong impact on the subsequent fate of the oil in the environment (Johansen 2003).

Large droplets (>1.0 mm) will rise rapidly and come to the surface relatively close to the discharge location, while small droplets (< 0.1 mm) will rise more slowly and can be transported long distances from the discharge location with ambient currents before reaching the sea surface. The smaller droplets will be kept suspended in the water column for a longer time than predicted by their rise velocity due to turbulence in the ocean. Oil droplets in the water column are subjected to enhanced dissolution and biodegradation compared to surface oil. Releases which are predominantly producing large droplets (in the millimeter size range) may thus result in relatively thick surface oil slicks, while thin surface films may be expected from releases producing small droplets (micron range). Thin oil films may not form water-in oil emulsions and will thus be more susceptible to natural dispersion. This implies that thin films will have distinctly shorter persistence on the sea surface than thicker oil slicks, and the possibility of oiling of adjacent shorelines may thus be strongly reduced (Johansen et al. 2013). However, factors like vertical turbulence mixing in the water column and cross flows will contribute to keep such fine droplets submerged for even more prolonged periods (Johansen et al. 2003).

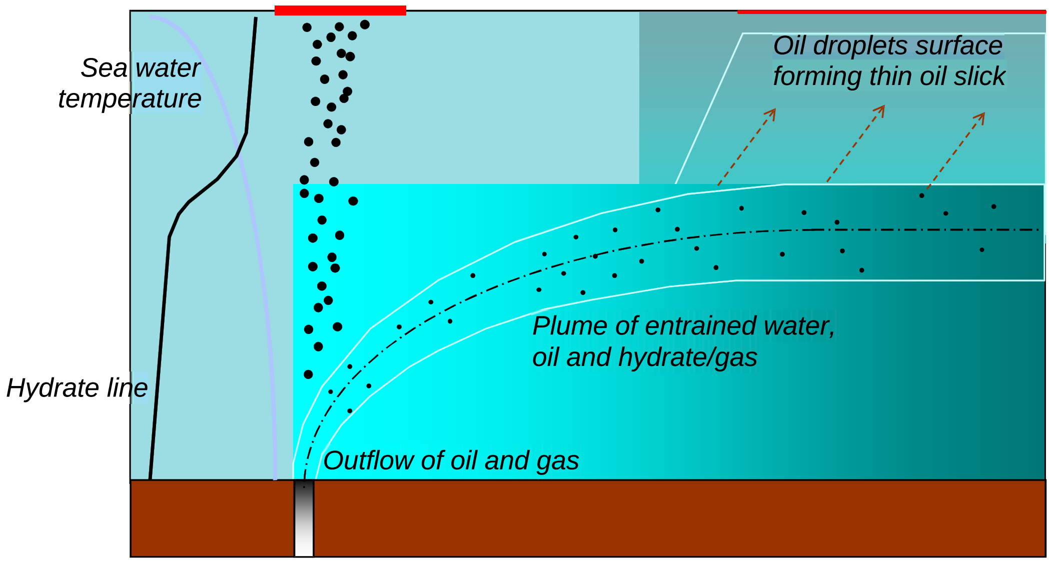

Figure 4.1. Simplified sketch of a modelled deep water plume. The oil and gas form a buoyancy driven plume which may be trapped at depth, as in this figure. Large oil droplets escape the plume and are transported to the surface as a function of their size and corresponding buoyancy. Both large (untreated) and smaller droplets after subsea dispersant injection (SSDI) are illustrated on the simplified figure.

Depending on the depth, the release rate, and the amount of gas in the release, a plume generated from a subsurface blowout may terminate in the water column or reach the sea surface. In blowouts from a few hundred meters or less with a large amount of gas (GOR > 50 at actual depth), the buoyancy generated by the expanding gas will tend to bring the plume of entrained water to the sea surface together with dispersed oil droplets and gas bubbles regardless of the initial oil droplet size generated at the source. A relatively thin surface oil slick will then form as the dispersed oil droplets settle out of the outward flow of the surfacing entrained water. A deep-water plume (with reduced buoyancy, due to gas compression and dissolution of the gas) is more likely to be trapped by the ambient density stratification or bent over by cross-flow. In this case oil droplets will separate from the plume and rise to the surface with their own terminal velocities determined by the size of the droplets as indicated in Figure 4.1.

4.2 Prediction of droplet size distributions

A model for the prediction of oil droplet size distribution during a mixed oil and gas release, with and without subsea injection of dispersants, is described in Johansen et al. 2013.

This droplet size distribution follows a Rosin-Rammler (Weibull) distribution and can be characterized by a median droplet size d50, given by a modified Weber number (We*) scaling:

$$d_{50}/D = A \, [We^*(\rho, U, \sigma ow, \mu)]^{-3/5} \qquad (1)$$

Where $We^* = We / [1 + B \, Vi \, (d50/D)^{1/3}]$.

D is here the outlet diameter, A and B are empirical constants calibrated against laboratory experiments (see Joahnsen et al. 2013) and Vi is the viscosity number ($\mu/\sigma ow$). Thus, the modified Weber number takes into account the oil density ρ, outlet velocity U, oil-water interfacial tension σow and oil viscosity μ.

The model presented in Eq. 1 covers cases with momentum jets and single fluid releases (oil only). For combined releases with gas and oil, a void fraction correction of the release velocity (Un) as described in Eq. 2 is used.

$$Un = Uoil / (1 - n)^{1/2}, \qquad (2)$$

Where n is the gas volume fraction.

To adjust for releases that are buoyancy dominated, an exit Froude number correction is applied, as described in Eq. 3.

$$UC = Un \, (1 + Fr^{-1}), \qquad (3)$$

Where $Fr = Un / (g' D)^{1/2}$ with $g' = g \, [\rho w - \rho oil \, (1 - n)]/\rho w$. Further details are found in Johansen et al. 2013.

The implementation of the modified Weber scaling in OSCAR takes into account the adjustments of outlet velocity U as given in equations 2 and 3 above. In this text this velocity is referred to as the buoyancy corrected velocity.

The modified Weber algorithm is based on a sound physical understanding on the involved physical processes and extensive datasets from laboratory testing with combined releases, various scales and testing under high pressure with combined releases with natural gas and live oil (Brandvik et al. 2016a, 2016b and 2017). The modified Weber scaling is today implemented in a large number of commercial and academic models for subsea releases (Socolofsky et al. 2015). Calculating droplet size predictions from the algorithm may be useful during blowout monitoring and data analysis if sufficient information is available.

5 Subsea Dispersant Application Monitoring Operational Guidelines

5.1 Introduction to Subsea Dispersant Operations

To understand how to use the SilCam, a basic understanding of the subsea dispersant injection operations is useful:

- A surface vessel carries and supplies dispersants to the spill site.
- Dispersant is injected from the surface vessel through a line that is connected to a nozzle held at the spill source by a Remotely Operated (Underwater) Vehicle (ROV).
- The ROV positions the nozzle to directly inject dispersant into the flow of oil as close to the release as shown in Figure 5.
- Dispersant is pumped at a controlled rate from the deck of the surface vessel through the nozzle and into the oil.
- Alternatively, well-capping structures can be equipped with built-in dispersant injection ports built in to facilitate dispersant application in some instances. This monitoring plan is adaptable and applicable to this type of subsea injection as well.

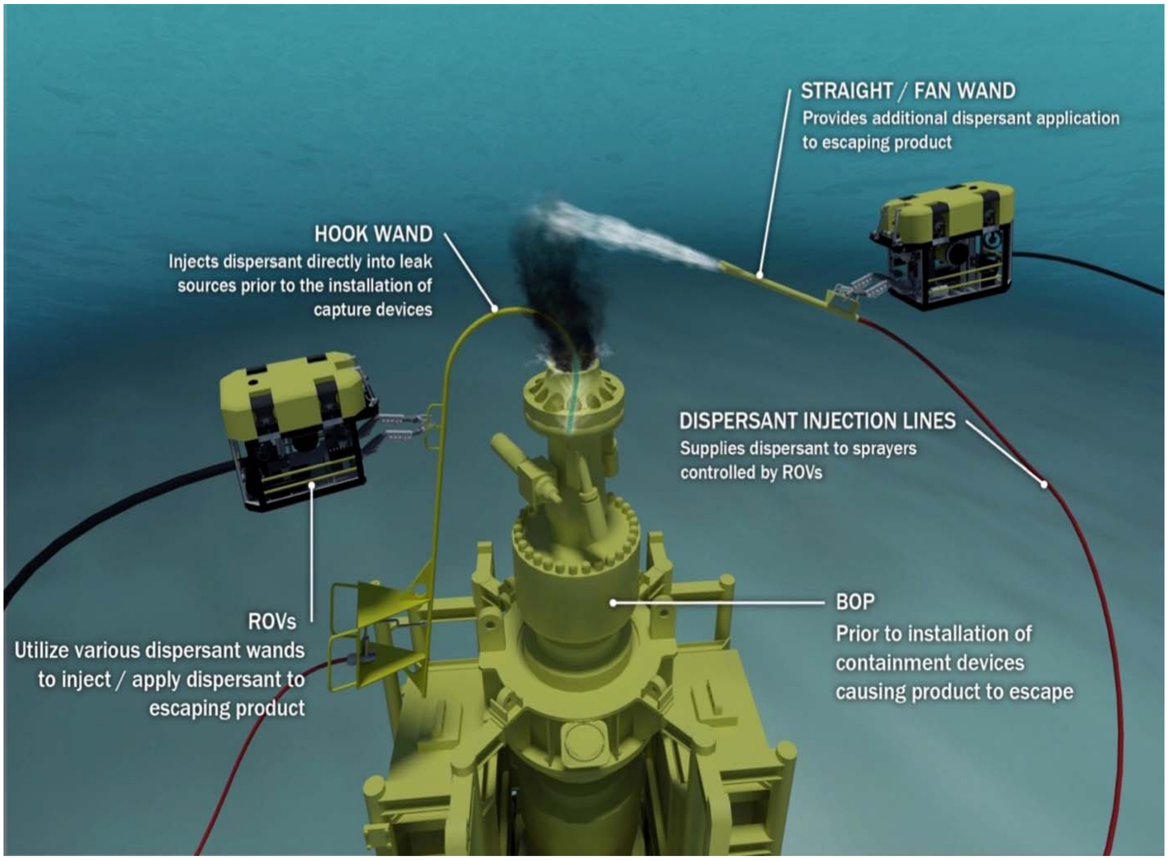

Figure 5. Examples of different subsea dispersant application.

The overall subsea dispersants monitoring program discussed in the NRT and API documents is designed to complement the dispersant application program and is divided into three phases, organized chronologically, and in increasing level of complexity: confirmation of dispersant efficacy (phase 1), delineation of resultant dispersed oil plumes (phase 2), and chemical characterization of dispersed oil in the water column (phase 3).

SilCam monitoring addresses oil and gas plume characterization and dispersant efficacy (phase 1) only. If a SilCam is available, it can be an alternate for the phase 1 monitoring guidance as described in API TR 1152 since a SilCam can provide direct confirmation of subsea dispersant efficacy.

5.2 Confirmation of Dispersant Efficacy near the Discharge Point using SilCam

As discussed in API TR 1152, the initial question that needs to be answered by subsea dispersant application monitoring is, “Is the dispersant injection having an effect on oil droplet size?”

A significant oil droplet size reduction is a clear indicator that dispersant application is working. Large scale experiments show that reductions in droplet size of an order of magnitude are possible with effective dispersant application (for example a median droplet size reduction from 3.0 mm or 3,000 µm microns to 300 microns).

SilCam monitoring is conducted by mounting a SilCam monitor on a ROV such that the instrument is a meter or more out away from the ROV (see Figure 6) and placing the SilCam in the rising oil and gas plume above the discharge after some dilution at a height approximately one hundred times the diameter of the release orifice (for example, 40 meters above an oil and gas release discharging from an oil well orifice of 40 centimeters). The exact placement of the instrument is not possible to know ahead of time because it is dependent on release conditions. However, information on the saturation of the instrument sample volume is returned as part of the software when in the real-time analysis mode, and this should be used to direct an ROV pilot to optimize the position of the instrument. Saturation values of 100% will indicate more dilution (going higher in the plume) is needed. Detailed instructions on the SilCam instrument and software operation are in the *SilCam Operating Manual*, Appendix 1.

The SilCam is then used to measure oil droplet and gas bubble distributions by a SilCam operator working closely with the ROV operator to ensure the SilCam is best placed to make measurements.

Droplet/gas bubble measurements will need to be collected with and without dispersant application to determine the effect of the dispersant.

These oil droplet and gas droplet size data can be used for several purposes;

- Verification subsea dispersant is reducing droplet size
- Oil spill trajectory modelling input
- Optimization of dispersant application
- gas to oil ratio

Oil droplet and gas bubble characterization for purposes other than assessing dispersant efficacy may require placement of the ROV and SilCam in other locations in or near the plume.

Figure 6. SilCam mounted in front of an ROV for oil spill monitoring.

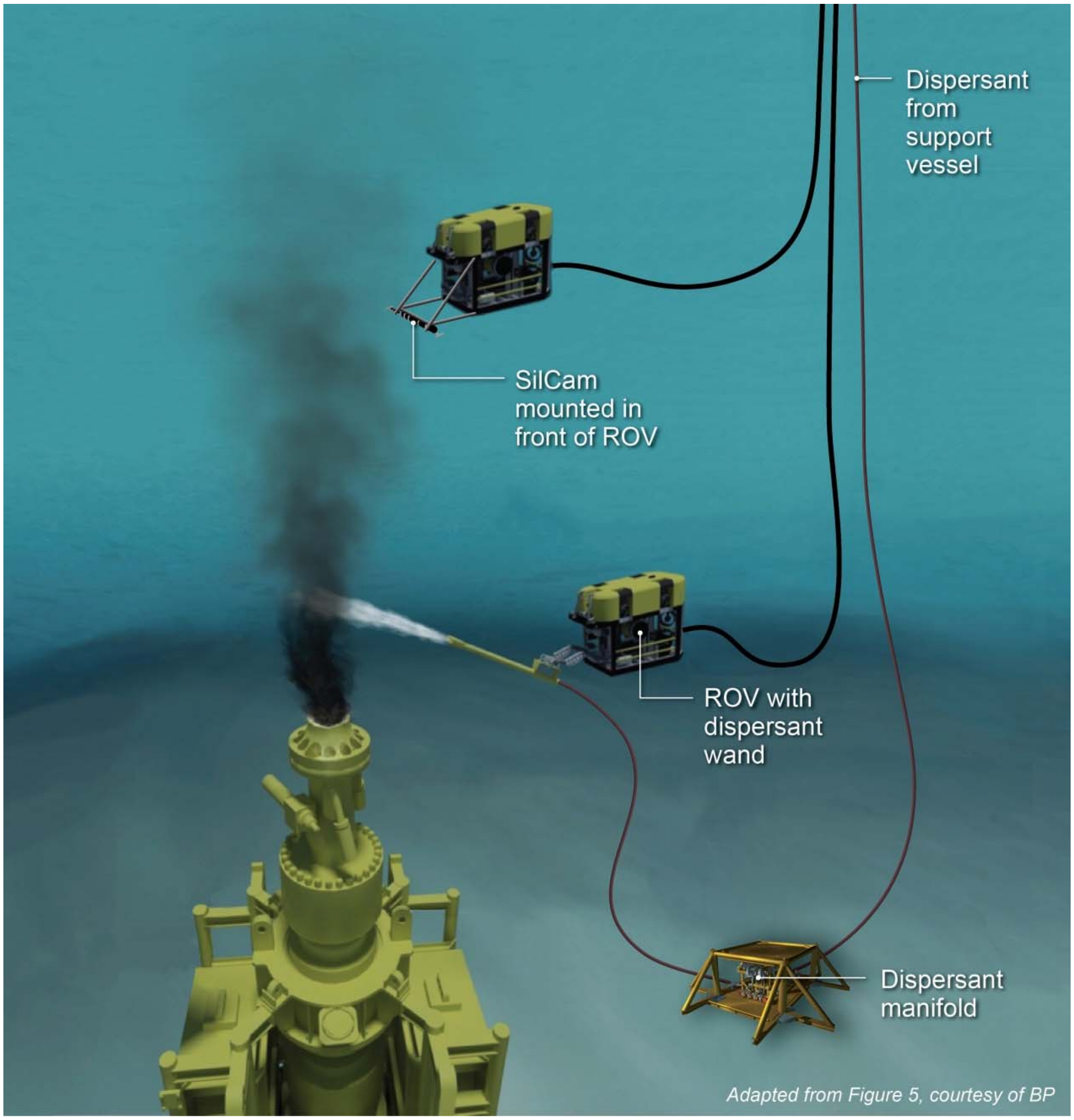

Figure 7. Placement of the SilCam in the rising oil plume to make droplet size measurements.

5.3 Basic Requirements List

- One ROV equipped with video camera– This ROV needs to be dedicated to monitoring dispersant effectiveness with a SilCam mounted forward of the ROV
- SilCam Monitor mounted and connected to ROV for data transmission and power
- Computer and necessary software for SilCam operation and data management
- Trained ROV operators
- Trained SilCam operators
- For full requirements refer to API TR 1152 to ensure vessel operation safety requirements are met

6 Data Interpretation and Data Management

6.1 Data Interpretation

SilCam data consists of files of droplet images which can be viewed or used to develop oil droplet and gas bubble size distributions and the instrument conditions when the data was collected. Droplet images, profiles of droplet size distribution, d50 volume of oil droplets and gas bubbles, and Gas to Oil Ratio (GOR) are all readily available using the SilCam software. Processed data can also be output as csv and other files type. These files can contain time-series size distributions of oil and gas, and be in a similar format to the size distributions produced by the LISST-100 or LISST-Holo instruments which can be easily handled in Excel, MatLab, Python, or other plotting tools. These calculations and data files can provide information relevant for:

- Dispersant application efficacy
    - Benefit of dispersant application can be understood by comparing mean oil droplet size without dispersant application to mean oil droplet size when dispersant is applied. Droplet size should be substantially reduced if dispersant is working.
    - Optimization of dispersant application - Application can be optimized by using oil droplet size data to monitor changes in mean oil droplet size as location of dispersant application equipment relative to the oil discharge is varied. Dispersant application rate can also be varied and oil droplet size monitored to identify the maximum oil droplet size reduction possible
- Oil spill trajectory modelling can use the actual SilCam oil droplet size distribution data for modelling transport and fate of the oil in the environment (oil droplet size will affect droplet rise rate in the ocean and affect when and where the oil droplets will rise to)
- Estimating GOR in the discharge – This can be obtained directly from the SilCam software data analysis and is expected to be $\pm$ 15%.

Summary figures can also be exported from the SilCam software in png format that can be used directly in reporting. These include: time-series d50s and GORs, example particle images, averaged size distributions of oil and gas.

6.2 Data Management

The Dispersant Efficacy Monitoring Plan will need to include a protocol addressing data management format and an accessible digital data storage platform mutually agreed upon by the UC. Data managers should be designated for ensuring the collection and distribution of all data monitoring elements.

7 Quality Assurance Project Plan

Consistent with other monitoring methods described in API TR 1152, the Quality Assurance Project Plan (QAPP) should address data collection methodology, handling, and chain of custody to ensure the highest quality data will be collected and maintained. The QAPP should be developed in accordance with EPA Quality Assurance Project Plans 4 and 5, and recommendations from the UC. The QAPP should also be based, as appropriate, on the NRT guidance on *Environmental Monitoring for Atypical Dispersant Operations*.

The QAPP will include:

- An introduction that identifies project objectives and the project staff.
- A site description and background which includes bathymetry, subsea currents (including temporal variations) and any other relevant features.
- A description of the SilCam monitoring protocols, data quality objectives, and any needed health and safety implementation strategies should be included in this monitoring plan.
- Quality assurance (QA) to address chain of custody procedures, field records including logs, and
- Qualitative data handling including photographs.

The SilCam instrument provides accurately sized images by design. This has been demonstrated by a benchmarking effort using spherical standards at 80 and 350 micron and direct comparison between SilCam and LISST while measuring oil droplets which is reported in the reference cited at the end of document.

The only calibration of the SilCam instrument required before use is to ensure the sample volume path length is accurate. The procedure for this calibration is described in the *SilCam Operating Manual* (Appendix 1).

The SilCam software has built-in automated tests for the SilCam analysis code, which must pass before new updates are incorporated. These tests include:

- Proper acquisition function.
- Configuration files are correctly read.
- Background image correction is performed.
- Tests for successful data processing and correctly formatted output files are produced.
- Correct d50 is returned from analysis of data of spherical standards of two different sizes.

As an additional safeguard, only SINTEF can approve software changes following peer review of the code. This ensures the accuracy of the software processing the data.

8 References

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Appendix 1

SilCam Operating Manual

Appendix C

Notes on experimental configurations for each run

Run	RUN000	GAS & WATER							
Release Setting	20	21	14	15	8	9	2	3	
Nozzle diameter (mm)	25	25	25	25	50	50	50	50	
L/min Oil	60	60	120	120	120	120	240	240	substitue oil for water
GOR	0,5	1	0,5	1	0,5	1	0,5	1	
Dispersant dosage (%)	0	0	0	0	0	0	0	0	
Est. d50 oil (um)	3000	2600	1400	1100	7200	5600	3700	2900	
Est. d50 gas (um)	4500	3900	2100	1650	10800	8400	5550	4350	
Tow speed (cm/s)	15	20	25	30	20	25	30	35	
Tow speed (kts)	0,291576	0,388768	0,48596	0,583152	0,388768	0,48596	0,583152	0,680344	
Horizontal seperation (m)	1	1,1	1,2	1,5	1,2	1,1	1,4	1,2	
Oil conc at meas. Loc. (uL/L)	6671	4172	3798	4499	9626	7871	3881	4285	
Oil lost (%)	0	0	0	0	0	0	0	0	
Gas lost (%)	88	80	53	28	82	64	69	46	
Runtime (sec)	60	60	60	60	60	60	60	60	
Run distance (m)	9	12	15	18	12	15	18	21	
Oil volume (L)	60	60	120	120	120	120	240	240	
Air volume (L)	30	60	60	120	60	120	120	240	
Dispersant (L)	0	0	0	0	0	0	0	0	
Total oil (L)	1080	water in this case							
Total air (L)	810								
Total dispersant (L)	0								
Total distance (m)	120								
Total time (min)	8								
Bridge seperation (m)	1,2125			Actual separation (m)			1,05		

Run	RUN001	GAS & WATER							
Release Setting	21	20	14	15	9	8	2	3	
Nozzle diameter (mm)	25	25	25	25	50	50	50	50	
L/min Oil	60	60	120	120	120	120	240	240	WATER
GOR	1	0,5	0,5	1	1	0,5	0,5	1	
Dispersant dosage (%)	0	0	0	0	0	0	0	0	
Est. d50 oil (um)	972	1107	593	501	2632	3007	1429	1254	
Est. d50 gas (um)	1458	1660,5	889,5	751,5	3948	4510,5	2143,5	1881	
Tow speed (cm/s)	22	16	25	30	28	20	30	35	
Tow speed (kts)	0,43	0,31	0,49	0,58	0,54	0,39	0,58	0,68	
Horizontal seperation (m)	1,5	1,3	1,2	1,5	1,5	1,2	1,4	1,2	
Oil conc at meas. Loc. (uL/L)	5644	8323	3798	4499	8300	9626	3881	4285	
Oil lost (%)	0	0	0	0	0	0	0	0	
Gas lost (%)	89	93	53	28	64	82	69	46	
Runtime (sec)	60	60	60	60	60	60	60	60	
Run distance (m)	13,2	9,6	15	18	16,8	12	18	21	
Oil volume (L)	60	60	120	120	120	120	240	240	
Air volume (L)	60	30	60	120	120	60	120	240	
Dispersant (L)	0	0	0	0	0	0	0	0	
Total oil (L)	1080	water in this case							
Total air (L)	810								
Total dispersant (L)	0								
Total distance (m)	123,6								
Total time (min)	8								
Bridge seperation (m)	1,35			Actual separation (m)			1,05		

Run	RUN002	OIL						
Release Setting	19	20	21	14	15	13		
Nozzle diameter (mm)	25	25	25	25	25	25		
L/min Oil	60	60	60	120	120	120		
GOR	0	0,5	1	0,5	1	0		
Gas dosage (L/min)	0	30	60	60	120	0		
Dispersant dosage (%)	0	0	0	0	0	0		
Est. d50 oil (um)	1601	1339	1176	610	536	723		
Est. d50 gas (um)	2401,5	2008,5	1764	915	804	1084,5		
Tow speed (cm/s)	14	18	22	26	30	20		
Tow speed (kts)	0,27	0,35	0,43	0,51	0,58	0,39		
Horizontal seperation (m)	1,3	1,1	1,1	1,1	1,1	1,2		
Oil conc at meas. Loc. (uL/L)	1514	3150	3120	6588	5897	4500		
Oil lost (%)	76	40	26	2	0,1	46		
Gas lost (%)	n/a	84	77	47	28	n/a		
Runtime (sec)	60	60	60	60	60	60		
Run distance (m)	8,4	10,8	13,2	15,6	18	12		
Oil volume (L)	60	60	60	120	120	120		
Air volume (L)	0	30	60	60	120	0		
Dispersant (L)	0	0	0	0	0	0		
Total oil (L)	540	143 Gallons						
Total air (L)	270							
Total dispersant (L)	0							
Total distance (m)	78							
Total time (min)	6							
Bridge seperation (m)	1,15			Actual separation (m)			1,05	

Run	RUN003	OIL							
Release Setting	7	8	9	13	14	15	19	20	21
Nozzle diameter (mm)	50	50	50	25	25	25	25	25	25
L/min Oil	120	120	120	120	120	120	60	60	60
GOR	0	0,5	1	0	0,5	1	0	0,5	1
Gas dosage (L/min)	0	60	120	0	60	120	0	30	60
Dispersant dosage (%)	0	0	0	0	0	0	0	0	0
Est. d50 oil (um)	4350	3552	3106	723	610	536	1601	1339	1176
Est. d50 gas (um)	6525	5328	4659	1084,5	915	804	2401,5	2008,5	1764
Tow speed (cm/s)	17	23	27	20	26	30	14	18	22
Tow speed (kts)	0,33	0,45	0,52	0,39	0,51	0,58	0,27	0,35	0,43
Horizontal seperation (m)	1,2	1,1	1,1	1,2	1,1	1,1	1,3	1,1	1,1
Oil conc at meas. Loc. (uL/L)	1450	4802	5568	4500	6588	5897	1514	3150	3120
Oil lost (%)	85,7	38	18	46	2	0,1	76	40	26
Gas lost (%)	n/a	71	58	n/a	47	28	n/a	84	77
Runtime (sec)	60	60	60	60	60	60	60	60	60
Run distance (m)	10,2	13,8	16,2	12	15,6	18	8,4	10,8	13,2
Oil volume (L)	120	120	120	120	120	120	60	60	60
Air volume (L)	0	60	120	0	60	120	0	30	60
Dispersant (L)	0	0	0	0	0	0	0	0	0
Total oil (L)	900		Gallons						
Total air (L)	450								
Total dispersant (L)	0								
Total distance (m)	118,2								
Total time (min)	9								
Bridge seperation (m)	1,144444				Actual separation (m)		1,05		

Run	RUN004	OIL & DISP.	
Release Setting	17	18	
Nozzle diameter (mm)	25	25	
L/min Oil	120	120	
GOR	0,5	1	
Dispersant dosage (%)	1	1	
Est. d50 oil (um)	100	89	
Est. d50 gas (um)	150	133,5	
Tow speed (cm/s)	101	120	
Tow speed (kts)	1,96	2,33	
Horizontal seperation (m)	12,3	12,5	
Oil conc at meas. Loc. (uL/L)	1090	915	
Oil lost (%)	0	0	
Gas lost (%)	18,3	17,5	
Runtime (sec)	60	60	
Run distance (m)	60,6	72	
Oil volume (L)	120	120	
Air volume (L)	60	120	
Dispersant (L)	1,2	1,2	
Total oil (L)	240	63 Gallons	
Total air (L)	180		
Total dispersant (L)	2,4	1 Gallons	
Total distance (m)	132,6		
Total time (min)	2		
Bridge seperation (m)	12,4		

Run	RUN005	OIL	
Release Setting	1	2	3
Nozzle diameter (mm)	50	50	50
L/min Oil	240	240	240
GOR	0	0,5	1
Gas dosage (L/min)	0	120	240
Dispersant dosage (%)	0	0	0
Est. d50 oil (um)	4600	3700	2900
Est. d50 gas (um)	6900	5550	4350
Tow speed (cm/s)	26	36	42
Tow speed (kts)	0,51	0,70	0,82
Horizontal seperation (m)	1,6	1,6	1,6
Oil conc at meas. Loc. (uL/L)	2482	5580	6430
Oil lost (%)	78	31	7,6
Gas lost (%)	n/a	67,5	54
Runtime (sec)	60	60	60
Run distance (m)	15,6	21,6	25,2
Oil volume (L)	240	240	240
Air volume (L)	0	120	240
Dispersant (L)	0	0	0
Total oil (L)	720	190 Gallons	
Total air (L)	360		
Total dispersant (L)	0		
Total distance (m)	62,4		
Total time (min)	3		
Bridge seperation (m)	1,6		

Run	**RUN006**	**OIL & DISP.**	
Release Setting	22	16	10
Nozzle diameter (mm)	25	25	50
L/min Oil	60	120	120
GOR	0	0	0
Gas dosage (L/min)	0	0	0
Dispersant dosage (%)	1	1	1
Est. d50 oil (um)	250	120	600
Est. d50 gas (um)	375	180	900
Tow speed (cm/s)	49	65	59
Tow speed (kts)	0,95	1,26	1,15
Horizontal seperation (m)	10,1	10,1	10,1
Oil conc at meas. Loc. (uL/L)	1125	1716	1572
Oil lost (%)	0	0	10,4
Gas lost (%)	n/a	n/a	n/a
Runtime (sec)	60	60	60
Run distance (m)	29,4	39	35,4
Oil volume (L)	60	120	120
Air volume (L)	0	0	0
Dispersant (L)	0,6	1,2	1,2
Total oil (L)	300	79 Gallons	
Total air (L)	0		
Total dispersant (L)	3		
Total distance (m)	103,8		
Total time (min)	3		
Bridge seperation (m)	10,1		
Run	**RUN007**	**OIL & DISP.**	
Release Setting	4	24	23
Nozzle diameter (mm)	50	25	25
L/min Oil	240	60	60
GOR	0	1	0,5
Gas dosage (L/min)	0	60	30
Dispersant dosage (%)	1	1	1
Est. d50 oil (um)	310	182	206
Est. d50 gas (um)	465	273	309
Tow speed (cm/s)	51	52	44
Tow speed (kts)	0,99	1,01	0,86
Horizontal seperation (m)	7,7	7,6	7,6
Oil conc at meas. Loc. (uL/L)	2381	613	728
Oil lost (%)	0	0	0
Gas lost (%)	n/a	15,5	19,2
Runtime (sec)	60	60	60
Run distance (m)	30,6	31,2	26,4
Oil volume (L)	240	60	60
Air volume (L)	0	60	30
Dispersant (L)	2,4	0,6	0,6
Total oil (L)	360	95 Gallons	
Total air (L)	90		
Total dispersant (L)	3,6		
Total distance (m)	88,2		
Total time (min)	3		
Bridge seperation (m)	7,633333		
Run	**RUN008**	**OIL & DISP.**	
Release Setting	5	6	17
Nozzle diameter (mm)	50	50	25
L/min Oil	240	240	120
GOR	0,5	1	0,5
Gas dosage (L/min)	120	240	60
Dispersant dosage (%)	1	1	1
Est. d50 oil (um)	292	224	100
Est. d50 gas (um)	438	336	150
Tow speed (cm/s)	70	82	58
Tow speed (kts)	1,36	1,59	1,13
Horizontal seperation (m)	7,7	7,7	7,7
Oil conc at meas. Loc. (uL/L)	1726	1472	1110
Oil lost (%)	0	0	0,3
Gas lost (%)	11,8	10,2	15,4
Runtime (sec)	60	60	60
Run distance (m)	42	49,2	34,8
Oil volume (L)	240	240	120
Air volume (L)	120	240	60
Dispersant (L)	2,4	2,4	1,2
Total oil (L)	600	159 Gallons	
Total air (L)	420		
Total dispersant (L)	6		
Total distance (m)	126		
Total time (min)	3		
Bridge seperation (m)	7,7		

Run	RUN009	OIL & DISP.	
Release Setting	11	12	18
Nozzle diameter (mm)	50	50	25
L/min Oil	120	120	120
GOR	0,5	1	1
Gas dosage (L/min)	60	120	120
Dispersant dosage (%)	1	1	1
Est. d50 oil (um)	481	421	115
Est. d50 gas (um)	721,5	631,5	172,5
Tow speed (cm/s)	52	62	68
Tow speed (kts)	1,01	1,21	1,32
Horizontal seperation (m)	7,7	7,5	7,7
Oil conc at meas. Loc. (uL/L)	686	827	944
Oil lost (%)	41,5	15,9	0
Gas lost (%)	59,9	34,4	14,4
Runtime (sec)	60	60	60
Run distance (m)	31,2	37,2	40,8
Oil volume (L)	120	120	120
Air volume (L)	60	120	120
Dispersant (L)	1,2	1,2	1,2
Total oil (L)	360	95 Gallons	
Total air (L)	300		
Total dispersant (L)	3,6		
Total distance (m)	109,2		
Total time (min)	3		
Bridge seperation (m)	7,633333		

Run	RUN010	OIL & DISP.	
Release Setting	22	16	10
Nozzle diameter (mm)	25	25	50
L/min Oil	60	120	120
GOR	0	0	0
Gas dosage (L/min)	0	0	0
Dispersant dosage (%)	1	1	1
Est. d50 oil (um)	250	120	600
Est. d50 gas (um)	375	180	900
Tow speed (cm/s)	31	42	38
Tow speed (kts)	0,60	0,82	0,74
Horizontal seperation (m)	7,2	7,6	7,5
Oil conc at meas. Loc. (uL/L)	1048	1555	1311
Oil lost (%)	0	0	18,2
Gas lost (%)	n/a	n/a	n/a
Runtime (sec)	60	60	60
Run distance (m)	18,6	25,2	22,8
Oil volume (L)	60	120	120
Air volume (L)	0	0	0
Dispersant (L)	0,6	1,2	1,2
Total oil (L)	300	79 Gallons	
Total air (L)	0		
Total dispersant (L)	3		
Total distance (m)	66,6		
Total time (min)	3		
Bridge seperation (m)	7,433333		

Run	RUN011	GAS & WATER		
Release Setting	23	24	17	18
Nozzle diameter (mm)	25	25	25	25
L/min Oil	60	60	120	120
GOR	0,5	1	0,5	1
Gas dosage (L/min)	30	60	60	120
Dispersant dosage (%)	0	0	0	0
Est. d50 oil (um)	3000	2600	1400	1100
Est. d50 gas (um)	4500	3900	2100	1650
Tow speed (cm/s)	44	52	58	68
Tow speed (kts)	0,85529	1,010797	1,127427	1,321811
Horizontal seperation (m)	7,6	7,6	7,7	7,7
Oil conc at meas. Loc. (uL/L)	728	613	1110	944
Oil lost (%)	0	0	0,3	0
Gas lost (%)	19,2	15,5	15,4	14,4
Runtime (sec)	60	60	60	60
Run distance (m)	26,4	31,2	34,8	40,8
Oil volume (L)	60	60	120	120
Air volume (L)	30	60	60	120
Dispersant (L)	0,6	0,6	1,2	1,2
Total oil (L)	360	95 Gallons		water
Total air (L)	270			
Total dispersant (L)	3,6			
Total distance (m)	133,2			
Total time (min)	4			
Bridge seperation (m)	7,65			

Run	RUN012	GAS & WATER		
Release Setting	23	24	17	18
Nozzle diameter (mm)	25	25	25	25
L/min Oil	60	60	120	120
GOR	0,5	1	0,5	1
Gas dosage (L/min)	30	60	60	120
Dispersant dosage (%)	1	1	1	1
Est. d50 oil (um)	206	182	100	115
Est. d50 gas (um)	309	273	150	172,5
Tow speed (cm/s)	44	52	58	68
Tow speed (kts)	0,85529	1,010797	1,127427	1,321811
Horizontal seperation (m)	7,6	7,6	7,7	7,7
Oil conc at meas. Loc. (uL/L)	728	613	1110	944
Oil lost (%)	0	0	0,3	0
Gas lost (%)	19,2	15,5	15,4	14,4
Runtime (sec)	60	60	60	60
Run distance (m)	26,4	31,2	34,8	40,8
Oil volume (L)	60	60	120	120
Air volume (L)	30	60	60	120
Dispersant (L)	0,6	0,6	1,2	1,2
Total oil (L)	360	95 Gallons		water
Total air (L)	270			
Total dispersant (L)	3,6			
Total distance (m)	133,2			
Total time (min)	4			
Bridge seperation (m)	7,65			

Run	RUN013	GAS & WATER			
Release Setting	23	24	17	18	
Nozzle diameter (mm)	50	50	50	50	Muffler on nozzle for air release
L/min Oil	120	120	240	240	
GOR	0,5	1	0,5	1	
Gas dosage (L/min)	30	60	120	240	
Dispersant dosage (%)	0	0	0	0	
Est. d50 oil (um)	7200	5600	3700	2900	
Est. d50 gas (um)	10800	8400	5550	4350	
Tow speed (cm/s)	50	50	50	50	
Tow speed (kts)	1	1	1	1	
Horizontal seperation (m)	7,6	7,6	7,7	7,7	
Oil conc at meas. Loc. (uL/L)					
Oil lost (%)					
Gas lost (%)					
Runtime (sec)	60	60	60	60	
Run distance (m)	30	30	30	30	
Oil volume (L)					
Air volume (L)					
Dispersant (L)					
Total oil (L)				water	
Total air (L)					
Total dispersant (L)					
Total distance (m)	120				
Total time (min)	4				
Bridge seperation (m)	7,7				

Run	RUN014	GAS & WATER			
Release Setting	32	31	30	29	
Nozzle diameter (mm)	50	50	50	50	
L/min Oil	240	240	120	120	water
GOR	1	0,5	1	0,5	
Gas dosage (L/min)	240	120	120	60	
Dispersant dosage (%)	1	1	1	1	
Est. d50 oil (um)	231	262	415	482	
Est. d50 gas (um)	346,5	393	622,5	723	
Tow speed (cm/s)	77	62	59	44	
Tow speed (kts)	1,50	1,21	1,15	0,86	
Horizontal seperation (m)	7,8	7,8	7,9	7,8	
Oil conc at meas. Loc. (uL/L)	2424	3016	1576	2132	
Oil lost (%)	0	0	0	0	
Gas lost (%)	11,1	13,5	34,7	66,8	
Runtime (sec)	60	60	60	40	
Run distance (m)	46,2	37,2	35,4	17,6	
Oil volume (L)	240	240	120	80	
Air volume (L)	240	120	120	40	
Dispersant (L)	2,4	2,4	1,2	0,8	
Total oil (L)	680	180 Gallons		water	
Total air (L)	520				
Total dispersant (L)	6,8				
Total distance (m)	136,4				
Total time (min)	3,666667				
Bridge seperation (m)	7,825				

Run	RUN015	OIL & DISP.		
Release Setting	22	23	24	18
Nozzle diameter (mm)	25	25	25	25
L/min Oil	60	60	60	120
GOR	0	0,5	1	1
Gas dosage (L/min)	0	30	60	120
Dispersant dosage (%)	1	1	1	1
Est. d50 oil (um)	282	206	182	114
Est. d50 gas (um)	423	309	273	171
Tow speed (cm/s)	32	44	52	68
Tow speed (kts)	0,62	0,86	1,01	1,32
Horizontal seperation (m)	7,9	7,7	7,6	7,7
Oil conc at meas. Loc. (uL/L)	282	239	214	976
Oil lost (%)	0,3	0	0	0
Gas lost (%)	n/a	19,6	15,5	14,6
Runtime (sec)	60	60	60	60
Run distance (m)	19,2	26,4	31,2	40,8
Oil volume (L)	60	60	60	120
Air volume (L)	0	30	60	120
Dispersant (L)	0,6	0,6	0,6	1,2
Total oil (L)	300	79 Gallons		
Total air (L)	210			
Total dispersant (L)	3			
Total distance (m)	117,6			
Total time (min)	4			
Bridge seperation (m)	7,725			

Run	RUN016	OIL & DISP.	
Release Setting	5	6	11
Nozzle diameter (mm)	50	50	50
L/min Oil	240	240	120
GOR	0,5	1	0,5
Gas dosage (L/min)	120	240	60
Dispersant dosage (%)	1	1	1
Est. d50 oil (um)	292	224	481
Est. d50 gas (um)	438	336	721,5
Tow speed (cm/s)	70	82	52
Tow speed (kts)	1,360688	1,593949	1,010797
Horizontal seperation (m)	7,7	7,7	7,7
Oil conc at meas. Loc. (uL/L)	1726	1472	686
Oil lost (%)	0	0	41,5
Gas lost (%)	11,8	10,2	59,9
Runtime (sec)	60	60	60
Run distance (m)	42	49,2	31,2
Oil volume (L)	240	240	120
Air volume (L)	120	240	60
Dispersant (L)	2,4	2,4	1,2
Total oil (L)	600	159 Gallons	
Total air (L)	420		
Total dispersant (L)	6		
Total distance (m)	122,4		
Total time (min)	3		
Bridge seperation (m)	7,7		

Run	RUN017	OIL	
Release Setting	1	2	3
Nozzle diameter (mm)	50	50	50
L/min Oil	240	240	240
GOR	0	0,5	1
Gas dosage (L/min)	0	120	240
Dispersant dosage (%)	0	0	0
Est. d50 oil (um)	4600	3700	2900
Est. d50 gas (um)	6900	5550	4350
Tow speed (cm/s)	26	36	42
Tow speed (kts)	0,51	0,70	0,82
Horizontal seperation (m)	1,6	1,6	1,6
Oil conc at meas. Loc. (uL/L)	2482	5580	6430
Oil lost (%)	78	31	7,6
Gas lost (%)	n/a	67,5	54
Runtime (sec)	60	60	60
Run distance (m)	15,6	21,6	25,2
Oil volume (L)	240	240	240
Air volume (L)	0	120	240
Dispersant (L)	0	0	0
Total oil (L)	720	190 Gallons	
Total air (L)	360		
Total dispersant (L)	0		
Total distance (m)	62,4		
Total time (min)	3		
Bridge seperation (m)	1,6		

Run	RUN018	OIL							
Release Setting	7	8	9	13	14	15	19	20	21
Nozzle diameter (mm)	50	50	50	25	25	25	25	25	25
L/min Oil	120	120	120	120	120	120	60	60	60
GOR	0	0,5	1	0	0,5	1	0	0,5	1
Gas dosage (L/min)	0	60	120	0	60	120	0	30	60
Dispersant dosage (%)	0	0	0	0	0	0	0	0	0
Est. d50 oil (um)	9000	7200	5700	1700	1400	1224	3600	3000	2600
Est. d50 gas (um)	13500	10800	8550	2550	2100	1836	5400	4500	3900
Tow speed (cm/s)	13,23	7,94	7,94	7,94	7,94	7,94	7,94	10,58	10,58
Tow speed (kts)	0,25	0,15	0,15	0,15	0,15	0,15	0,15	0,20	0,20
Horizontal seperation (m)	1,2	1,1	1,1	1,2	1,1	1,1	1,3	1,1	1,1
Oil conc at meas. Loc. (uL/L)	1450	4802	5568	4500	6588	5897	1514	3150	3120
Oil lost (%)	85,7	38	18	46	2	0,1	76	40	26
Gas lost (%)	n/a	71	58	n/a	47	28	n/a	84	77
Runtime (sec)	60	60	60	60	60	60	60	60	60
Run distance (m)	10,2	13,8	16,2	12	15,6	18	8,4	10,8	13,2
Oil volume (L)	120	120	120	120	120	120	60	60	60
Air volume (L)	0	60	120	0	60	120	0	30	60
Dispersant (L)	0	0	0	0	0	0	0	0	0
Total oil (L)	900	238 Gallons							
Total air (L)	450								
Total dispersant (L)	0								
Total distance (m)	118,2								
Total time (min)	9								
Bridge seperation (m)	1,144444								

Runs 19-20 were used for SilCam training

Run	RUN021	GAS & WATER					
Release Setting	20	20	20	20	20	20	
Nozzle diameter (mm)	25	25	25	25	25	25	
L/min Oil	60	60	60	60	60	60	water
GOR	0,5	0,5	0,5	0,5	0,5	0,5	
Gas dosage (L/min)	30	30	30	30	30	30	
Dispersant dosage (%)	0	0	0	0	0	0	
Est. d50 oil (um)	3000	3000	3000	3000	3000	3000	
Est. d50 gas (um)	4500	4500	4500	4500	4500	4500	
Tow speed (cm/s)	60	50	40	30	20	10	
Tow speed (kts)	1,164	0,97	0,776	0,582	0,388	0,194	
Horizontal seperation (m)	1,6	1,6	1,6	1,6	1,6	1,6	
Oil conc at meas. Loc. (uL/L)	3150	3150	3150	3150	3150	3150	
Oil lost (%)	40	40	40	40	40	40	
Gas lost (%)	84	84	84	84	84	84	
Runtime (sec)	60	60	60	60	60	60	
Run distance (m)	36	30	24	18	12	6	
Oil volume (L)	60	60	60	60	60	60	
Air volume (L)	30	30	30	30	30	30	
Dispersant (L)	0	0	0	0	0	0	
Total oil (L)	360	95 Gallons		Water			
Total air (L)	180						
Total dispersant (L)	0						
Total distance (m)	126						
Total time (min)	6						
Bridge seperation (m)	1,6						

Run	RUN022	OIL				
Release Setting	20	20	20	20	20	20
Nozzle diameter (mm)	25	25	25	25	25	25
L/min Oil	60	60	60	60	60	60
GOR	0,5	0,5	0,5	0,5	0,5	0,5
Gas dosage (L/min)	30	30	30	30	30	30
Dispersant dosage (%)	0	0	0	0	0	0
Est. d50 oil (um)	3000	3000	3000	3000	3000	3000
Est. d50 gas (um)	4500	4500	4500	4500	4500	4500
Tow speed (cm/s)	50	40	30	20	10	5
Tow speed (kts)	0,97	0,776	0,582	0,388	0,194	0,097
Horizontal seperation (m)	1,6	1,6	1,6	1,6	1,6	1,6
Oil conc at meas. Loc. (uL/L)	3150	3150	3150	3150	3150	3150
Oil lost (%)	40	40	40	40	40	40
Gas lost (%)	84	84	84	84	84	84
Runtime (sec)	60	60	60	60	60	60
Run distance (m)	30	24	18	12	6	3
Oil volume (L)	60	60	60	60	60	60
Air volume (L)	30	30	30	30	30	30
Dispersant (L)	0	0	0	0	0	0
Total oil (L)	360	95 Gallons				
Total air (L)	180					
Total dispersant (L)	0					
Total distance (m)	93					
Total time (min)	6					
Bridge seperation (m)	1,6					

Run 23 was used for SilCam training

Run	RUN024	OIL				
Release Setting	20	20	20	20	20	20
Nozzle diameter (mm)	25	25	25	25	25	25
L/min Oil	60	60	60	60	60	60
GOR	0,5	0,5	0,5	0,5	0,5	0,5
Gas dosage (L/min)	30	30	30	30	30	30
Dispersant dosage (%)	0	0	0	0	0	0
Est. d50 oil (um)	3000	3000	3000	3000	3000	3000
Est. d50 gas (um)	4500	4500	4500	4500	4500	4500
Tow speed (cm/s)	50	40	30	20	10	5
Tow speed (kts)	0,97	0,776	0,582	0,388	0,194	0,097
Horizontal seperation (m)	1,6	1,6	1,6	1,6	1,6	1,6
Oil conc at meas. Loc. (uL/L)	3150	3150	3150	3150	3150	3150
Oil lost (%)	40	40	40	40	40	40
Gas lost (%)	84	84	84	84	84	84
Runtime (sec)	60	60	60	60	60	60
Run distance (m)	30	24	18	12	6	3
Oil volume (L)	60	60	60	60	60	60
Air volume (L)	30	30	30	30	30	30
Dispersant (L)	0	0	0	0	0	0
Total oil (L)	360	95 Gallons				
Total air (L)	180					
Total dispersant (L)	0					
Total distance (m)	93					
Total time (min)	6					
Bridge seperation (m)	1,6					

Run	RUN025	GAS & WATER					
Release Setting	11	11	11	11	11	11	
Nozzle diameter (mm)	50	50	50	50	50	50	
L/min Oil	120	120	120	120	120	120	water
GOR	0,5	0,5	0,5	0,5	0,5	0,5	
Gas dosage (L/min)	60	60	60	60	60	60	
Dispersant dosage (%)	1	1	1	1	1	1	
Est. d50 oil (um)	481	481	481	481	481	481	
Est. d50 gas (um)	721,5	721,5	721,5	721,5	721,5	721,5	
Tow speed (cm/s)	60	50	40	30	20	10	
Tow speed (kts)	1,164	0,97	0,776	0,582	0,388	0,194	
Horizontal seperation (m)	1,6	1,6	1,6	1,6	1,6	1,6	
Oil conc at meas. Loc. (uL/L)	686	686	686	686	686	686	
Oil lost (%)	41,5	41,5	41,5	41,5	41,5	41,5	
Gas lost (%)	59,9	59,9	59,9	59,9	59,9	59,9	
Runtime (sec)	60	60	60	60	60	60	
Run distance (m)	36	30	24	18	12	6	
Oil volume (L)	120	120	120	120	120	120	
Air volume (L)	60	60	60	60	60	60	
Dispersant (L)	1,2	1,2	1,2	1,2	1,2	1,2	
Total oil (L)	720	190 Gallons		Water			
Total air (L)	360						
Total dispersant (L)	7,2						
Total distance (m)	126						
Total time (min)	6						
Bridge seperation (m)	1,6						