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Project acronym: ¡VAMOS!
Project title: ¡Viable Alternative Mine Operating System!
Funding Scheme: Collaborative project
## Work Package
### Deliverable sheet

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<th>Full description</th>
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<tr>
<td>ADCP</td>
<td>Acoustic Doppler Current Profiler</td>
</tr>
<tr>
<td>ABS</td>
<td>Acoustic Backscatter</td>
</tr>
<tr>
<td>AUV</td>
<td>Autonomous Underwater Vehicle</td>
</tr>
<tr>
<td>AWAC</td>
<td>Acoustic Wave and Current meter</td>
</tr>
<tr>
<td>CC</td>
<td>Control Cabin</td>
</tr>
<tr>
<td>COTS</td>
<td>Commercial Off-the-Shelf</td>
</tr>
<tr>
<td>CPU</td>
<td>Central Processing Unit</td>
</tr>
<tr>
<td>CTD</td>
<td>Conductivity, Temperature, and Depth</td>
</tr>
<tr>
<td>DGPS</td>
<td>Differential Global Positioning System</td>
</tr>
<tr>
<td>DO</td>
<td>Dissolved Oxygen</td>
</tr>
<tr>
<td>EIA</td>
<td>Environmental Impact Assessment</td>
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<td>EMS</td>
<td>Environmental Monitoring System</td>
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<tr>
<td>EPA</td>
<td>Environmental Protection Agency</td>
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<tr>
<td>FEDPC</td>
<td>Fugro Environmental Data PC</td>
</tr>
<tr>
<td>FTU</td>
<td>Formazin Turbidity Unit (FTU)</td>
</tr>
<tr>
<td>g</td>
<td>Gravitational Acceleration (on Earth)</td>
</tr>
<tr>
<td>GB</td>
<td>Gigabyte</td>
</tr>
<tr>
<td>HMI</td>
<td>Human Machine Interface</td>
</tr>
<tr>
<td>HROV</td>
<td>Hybrid Remotely Operated Vehicle</td>
</tr>
<tr>
<td>INS</td>
<td>Inertial Navigation System</td>
</tr>
<tr>
<td>I/O</td>
<td>Input/Output</td>
</tr>
<tr>
<td>IP</td>
<td>Internet Protocol</td>
</tr>
<tr>
<td>JB</td>
<td>Junction Box</td>
</tr>
<tr>
<td>LARV</td>
<td>Launch and Recovery Vessel</td>
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<tr>
<td>LTS</td>
<td>Long Term Support</td>
</tr>
<tr>
<td>MPP</td>
<td>Multi-parameter probe</td>
</tr>
<tr>
<td>MSS</td>
<td>Mining Supervision System</td>
</tr>
<tr>
<td>MV</td>
<td>Mining Vehicle</td>
</tr>
<tr>
<td>NLS</td>
<td>National Laboratory Service</td>
</tr>
<tr>
<td>NTU</td>
<td>Nephelometric Turbidity Unit</td>
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<tr>
<td>NWS</td>
<td>National Weather Service</td>
</tr>
<tr>
<td>OBS</td>
<td>Optical Backscatter</td>
</tr>
<tr>
<td>OS</td>
<td>Operating System</td>
</tr>
<tr>
<td>PC</td>
<td>Personal Computer</td>
</tr>
<tr>
<td>PNAS</td>
<td>Positioning, Navigation and Awareness System</td>
</tr>
<tr>
<td>RAM</td>
<td>Random Access Memory</td>
</tr>
<tr>
<td>RIB</td>
<td>Rigid-hulled Inflatable Boat</td>
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<tr>
<td>ROS</td>
<td>Robot Operating System</td>
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<tr>
<td>SBC</td>
<td>Single Board Computer</td>
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<td>Abbreviation</td>
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<tr>
<td>SSC</td>
<td>Suspended Sediment Concentration</td>
</tr>
<tr>
<td>ST</td>
<td>Sub Task</td>
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<tr>
<td>TSS</td>
<td>Total Suspended Sediment</td>
</tr>
<tr>
<td>UKAS</td>
<td>United Kingdom Accreditation Service</td>
</tr>
<tr>
<td>VDI</td>
<td>Virtual Disk Image</td>
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<tr>
<td>VIPS</td>
<td>Voltammetric In-situ Profiling System</td>
</tr>
<tr>
<td>VM</td>
<td>Virtual Machine</td>
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<tr>
<td>VR</td>
<td>Virtual Reality</td>
</tr>
<tr>
<td>WP</td>
<td>Work Package</td>
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<td>WSL</td>
<td>Windows Subsystem for Linux</td>
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Executive Summary
The purpose of this document is to record the approach, methods and technology employed for sub-task ST4.1.2 Environmental Monitoring System, as specified in Grant Agreement, 642477, Annex 1 (Part A), Work Package 4 (WP4). The experimental approach to monitoring mining trials is explained, and the near-, mid-, far-field environmental monitoring methods and sensors are described. The relationship and interaction with other tasks, subtasks, and deliverables is also provided.

¡VAMOS! successfully trialed and evaluated a range of environmental monitoring technologies and approaches to support the environmental impact assessment (EIA) of future inland submerged mining projects. The trial results demonstrate that existing technologies and techniques are capable of supporting the EIA process, including real-time monitoring for important environmental parameters.

This deliverable documents the following project objectives and tasks:

1. The provision of a framework for environmental monitoring that encompasses appropriate methods and protocols for submerged mining.
2. Deployment of an environmental monitoring system before, during and after mining trials at Lee Moor, Devon, UK.
3. Deployment of an environmental monitoring system before, during and after mining trials at Silvermines in County Tipperary, Ireland.
4. The successful development and demonstration of a real-time environmental data broadcast and visualisation system.

The outputs from ST4.1.2 and Deliverable 4.2 have informed Task 6.3 and Deliverable 6.3 Environmental Impact Assessment. Recommendations for improvements to the full data pipeline for EIA purposes, including parameter selection, requisite sensor performance envelopes and deployment approaches are provided in D6.3. Potential applications to marine mining are also included, where relevant.

1 Introduction

1.1 Background to the ¡VAMOS! Project
Estimates indicate that the value of unexploited European marine mineral resources at a depth of 500-1,000 meters is ca €100 billion, however, a number of physical, economic, social, environmental and human constraints have as yet limited their exploitation. ¡VAMOS! will provide a new safe, clean and low visibility mining technique and will prove its economic viability for extracting currently unreachable mineral deposits, thus encouraging investment and helping to put the EU back on a level playing field in terms of access to strategically important minerals. Deriving from successful deep-sea mining techniques, the ¡VAMOS! mining solution aspires to lead to: re-opening abandoned mines; extensions of opencut mines which are limited by stripping ratio, hydrological or geotechnical problems; and opening of new mines in the EU. ¡VAMOS! will design and manufacture innovative automated
excavation equipment and environmental impact monitoring tools that will be used to perform field tests in two inland flooded mine sites in Europe with a range of rock hardness and pit morphology. The overall objectives described in the ¡VAMOS! project summary are to:

5. Develop a prototype underwater, remotely controlled, mining machine with associated launch and recovery equipment.
6. Enhance currently available underwater sensing, spatial awareness, navigational and positioning technology.
8. Conduct field trials with the prototype equipment in abandoned and inactive mine sites with a range of rock types and at a range of submerged depths.
9. Evaluate the productivity and cost of operation to enable mine-ability and economic reassessment of the EU's mineral resources.
10. Maximize impact and enable the Market Up-Take of the proposed solutions by defining and overcoming the practicalities of the concept, proving the operational feasibility and the economic viability.
11. Contribute to the social acceptance of the new extraction technique via public demonstrations in EU regions.

1.2 Purpose of this Document

The purpose of this document is to record the approach, methods and technology employed for sub-task ST4.1.2 Environmental Monitoring System.
2 Environmental Monitoring Framework

2.1 Objectives
This deliverable addresses the development of the environmental monitoring framework for the submerged mining operations as defined in ST4.1.2. To develop and assess the effectiveness of the framework the following key activities were conducted:

1. Assess available site-specific environmental data to scope and determine appropriate environmental parameters to monitor during mining trials, including turbidity, pH and salinity.
2. Formulate initial site-specific monitoring procedures, protocols and technology specifications, based on available data.
3. Baseline the mine sites before trials commence, according to the available site-specific environmental data.
4. Deploy multi-parameter sensors and collect water samples from optimal platforms for near-, mid- and far-field measurements during mining trials.
5. Assess and refine, if possible, environmental monitoring procedures, protocols and technology specifications, based on early and ongoing monitoring results.
6. Resurvey the extraction site after the cessation of mining trial disturbance to establish initial post-trial environmental parameter levels.
7. Document the lessons learned from field trials, and provide recommendations that will support the full environmental impact assessment process.

The outputs of ST4.1.2 and findings of D4.2 inform D5.5 and D6.3. Further details of the relationship with other relevant tasks and deliverables are provided in section 2.2 Task and Deliverable Dependencies.

The methods successfully demonstrated during the mining trials, and the corresponding lessons learned, provide an appropriate framework for the environmental monitoring of future submerged mining projects. The appropriateness of this framework is validated by the successful data acquisition documented in D5.5 Proof of Environmental Viability of the Submerged Mining Concept, and the development and demonstration of real time environmental monitoring technology. Technical recommendations for environmental monitoring are captured in D6.3 Environmental Impact Assessment.

The approach, methods and technologies documented in this deliverable support the following essential steps in the environmental impact assessment (EIA) process:

- Establishing environmental baselines.
- Operational environmental monitoring.
- Post-mining surveys.
2.1.1 Initial assessment of site-specific environmental data to scope and determine appropriate environmental parameters

From the project outset, as set out in the deliverables, the aim of the monitoring has been to determine appropriate environmental parameters to monitor, including turbidity, pH and salinity. As a new technology, there is no existing framework for the monitoring of submerged mining. For the project, there were several key questions to address:

- Existing data; what parameters were previously monitored and why?
- How can the effects of the trial be differentiated from background natural and anthropogenic levels and effects?
- Are the effects of the trial having a wider effect on the environment?
- What data would be useful if the mining were scaled up or undertaken elsewhere?
- The original plan for the ¡VAMOS! project was to include marine sites; can the methods and technology be transferred to coastal waters?
- Do other existing monitoring strategies exist that could be applied?
- What monitoring strategies are reasonably practicable, taking into account project timescales and budgets?

In response, Fugro elected to monitor a comprehensive suite of physical and chemical parameters, using proven and novel equipment, with a focus on real-time data provision where practicable. The aim was to incorporate some marine dredge monitoring approaches for physical parameters where relevant, but to also adapt existing monitoring techniques and apply entirely new techniques to optimise data acquisition for submerged mining. Full details of parameter selection are presented in section 3 Environmental Monitoring System Approach.

2.1.2 Develop initial site-specific monitoring procedures, protocols and technology specifications

As this is a research project investigating the impacts of a novel submerged mining technology, there is no established or widely-accepted body of scientific knowledge or best practice that could inform a priori sampling designs, methods and technology specifications.

The final recommendations for monitoring have been produced after analysis of environmental data collected during the trials, but the initial approach to monitoring comprises near-, mid- and far-field sampling during mining activities, with the aim of establishing the extent and concentrations of mining plumes and changes in water column chemistry caused by specific mining activities.

Initial monitoring procedures, protocols and survey designs were developed and tailored throughout the trial, as the site-specific mining plans were established as part of D5.1 Field Test Planning.
2.1.3 Baseline the mine sites before trials commence

It is best practice that environmental baselines should encompass the full range of seasonality (at least one year), however the compressed timelines of final site selections and management planning meant that this was not possible at either of the selected sites. As a result, Fugro conducted comprehensive baseline studies immediately prior to the mining trials, to avoid intervening environmental variation that could affect interpretation of changes in measured parameters.

Fugro deployed bed level (mine floor) in-water instrumentation and meteorological instrumentation, and collected water samples within each pit and in surrounding surface water bodies, before both trials and throughout the period of the mining activities, in order to assess the ability to discriminate between natural climatic and other environmental variability and specific impacts upon water chemistry.

2.1.4 Deploy multi-parameter sensors and collect water samples during mining trials

To measure and monitor physical and chemical changes to the water column caused by the mining vehicle during mining trials Fugro deployed a suite of sensors capable of working in the expected conditions and providing data suitable to support the ¡VAMOS! project. The multi-parameter sensors were deployed on the mining vehicle (MV), and profiled the water column from the launch and recovery vehicle (LARV) and from small surface vessels.

2.1.5 Monitoring during mining trials

Fugro tested a number of approaches to monitor the impact of mining activities. This monitoring focused on sediment plumes created by the mining activities and physical changes to the water chemistry. Monitoring comprised measurements from instrumentation across the mine floor and around the pit perimeter, MV-installed instruments, and vessel-based measurements and samples. Instrument and sample data were then related to mining activity datasets.

2.1.6 Post-trial survey

Fugro resurveyed all water bodies using the same technology and techniques two weeks after mining trials had finished. All surrounding sampling locations also had water samples taken at the same time. Mine floor instrumentation was left in situ for the intervening period.

2.1.7 Assessment of procedures, protocols and monitoring technologies deployed

During the Lee Moor mining trials, a wide range of monitoring technologies and techniques was deployed to assess the impact of mining activities. These monitoring technologies and techniques were evaluated for their relevance, suitability and effectiveness to support the EIA process. The experience gained during the Lee Moor trials subsequently informed the technology selection and sampling approach at Silvermines.

The evaluations at both sites considered the full data pipeline required to support robust and defensible environmental impact assessment. The findings of this deliverable help to provide a framework for environmental monitoring of submerged mining, informed by lessons learned from both complete mining trial monitoring life cycles, and documenting the monitoring and analysis of environmental parameters measured.
2.2 Task and Deliverable Dependencies

Deliverable 4.2 is informed, in part, by the outputs of D1.3 Zero-state environmental and geo-hazard evaluation criteria.

The mine plans formulated in D5.1 Field Test Planning were designed to support the near-, mid- and far-field monitoring survey design, as well as meeting the mining objectives.

The development of robust environmental monitoring techniques in ST4.1.2 will underpin Fugro’s activities as part of ST5.3.2: Mine the Deposit and Log Key Variables, and will support the findings of D5.5 Proof of Environmental Viability of the Submerged Mining Concept.

T6.3 Social and Environmental Impact integrates the field measurements taken during ST4.1.2 and relevant findings from environmental impact assessments of similar projects. D6.3 Environmental Impact Assessment then provides recommendations for impact assessment of submerged mining of other enclosed inland open pit mines.


3 Environmental Monitoring System Approach

The approaches adopted for the Environmental Monitoring System (EMS) at each trial site is summarised in Table 3.1. Equipment and application summaries are detailed in sections 3.1.1 to 3.2.4.

Table 3.1: ¡VAMOS! Environmental monitoring approach at Lee Moor and Silvermines.

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<tr>
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<th>Application</th>
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<th>Data availability</th>
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<tr>
<td></td>
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<td>Baseline</td>
<td>Operational</td>
<td>Post mining</td>
<td>Near</td>
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<tr>
<td>1200 kHz RDI ADCP</td>
<td>Transecting from vessel to determine SSC</td>
<td>Counts (ABS)¹</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
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<tr>
<td>1 MHz Nortek Aquapro</td>
<td>Bed mounted instrument at L1, located ~150 m from LARV</td>
<td>Counts (ABS)¹</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
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<tr>
<td>1 MHz Nortek Aquapro</td>
<td>Bed mounted instrument at L2/L3, located ~75 m from LARV</td>
<td>Counts (ABS)¹</td>
<td>x</td>
<td>x</td>
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<td>Aquatec Aqualogger 210 OBS</td>
<td>Bed mounted instrument at L1, located ~150 m from LARV</td>
<td>FTU¹, Temperature</td>
<td>x</td>
<td>x</td>
<td>x</td>
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<tr>
<td>Aquatec Aqualogger 210 OBS</td>
<td>Bed mounted instrument at L2/L3, located ~75 m from LARV</td>
<td>FTU¹, Temperature</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Idronaut EA89 CTD</td>
<td>Multiparameter probe used for water quality profiling from a vessel, and also integrated with the VIPS to provide real-time data from the MV</td>
<td>FTU¹, Temperature, Conductivity, Salinity², pH, Dissolved Oxygen</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Idronaut VIPS</td>
<td>Voltammetric in-situ profiling system. Used to collect trace heavy metal concentration data from a vessel and also mounted to the MV</td>
<td>mV (to determine Cu(II), Pb(II), Cd(II), Zn(II), Mn(II))</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Water samples</td>
<td>Water samples processed in laboratory off site. Samples at depth taken with Niskin, surface samples taken directly</td>
<td>Conductivity, pH, BOD, COD, SSC, Turbidity (NTU), Nitrogen Total as N, Nitrate, Nitrite, Chloride, Phosphate (Ortho), Phosphorous (Total), Silicate (Reactive), Sulphur, Calcium, Magnesium, Potassium, Sodium, Aluminium (Dissolved as Al), Aluminium (Total), Iron, Manganese, Copper, Zinc, Barium</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Valeport TideMaster</td>
<td>Water level sensor deployed on edge of water body</td>
<td>Pressure (dBar)</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Sensor</td>
<td>Application</td>
<td>Parameters</td>
<td>Phase</td>
<td>Location</td>
<td>Depth</td>
<td>Data availability</td>
</tr>
<tr>
<td>------------------------</td>
<td>------------------------------------------------------------------------------</td>
<td>-------------------------------------------------</td>
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<td>----------</td>
<td>------------------</td>
<td>-------------------</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Baseline</td>
<td>Operational</td>
<td>Post mining, Near, Mid, Far-field, Bed, Mid water, Surface, NA</td>
<td>x</td>
</tr>
<tr>
<td>Vaisala WXT520</td>
<td>Meteorological station used for rainfall only</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Sensor</strong></td>
<td><strong>Application</strong></td>
<td><strong>Parameters</strong></td>
<td><strong>Phase</strong></td>
<td><strong>Location</strong></td>
<td><strong>Depth</strong></td>
<td><strong>Data</strong></td>
</tr>
<tr>
<td>1 MHz</td>
<td>Nortek Aqualogger 310 TYPT OBS</td>
<td>Counts (ABS)¹</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td></td>
<td>Mounted on MV to determine SSC between 0 m - 20 m from MV</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aquatec Aqualogger</td>
<td>Mounted on MV to determine SSC between adjacent to MV</td>
<td>FTU¹, Temperature, Pressure</td>
<td>x</td>
<td>x</td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>210 OBS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Bed mounted instrument at L1, located 0 m - 50 m from LARV when MV was</td>
<td>FTU¹, Temperature</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td></td>
<td>mining in area A, 50 m to 150 m when MV was mining in area B</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aquatec Aqualogger</td>
<td>Surface mounted instrument at L1, located (horizontally) 0 m - 50 m</td>
<td>FTU¹, Temperature</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>210 OBS</td>
<td>from LARV when MV was mining in area A, 50 m to 150 m when MV was</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>mining in area B</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aquatec Aqualogger</td>
<td>Bed mounted instrument at L2, located 0 m - 50 m from LARV when MV was</td>
<td>FTU¹, Temperature</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>210 OBS</td>
<td>mining in area B, 50 m to 150 m when MV was mining in area B</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aquatec Aqualogger</td>
<td>Surface mounted instrument at L2, located (horizontally) 0 m - 50 m</td>
<td>FTU¹, Temperature</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>210 OBS</td>
<td>from LARV when MV was mining in area A, 50 m to 150 m when MV was</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>mining in area A</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Idronaut EA89 CTD</td>
<td>Multiparameter probe used for water quality profiling from a vessel, and</td>
<td>FTU¹, Temperature, Conductivity, Salinity², pH</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td></td>
<td>also integrated with the VIPS to provide real-time data from the MV</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Idronaut VIPS</td>
<td>Voltammetric in-situ profiling system. Used to collect trace heavy metal</td>
<td>mV (to determine Cu(II), Pb(II), Cd(II), Zn(II), Mn(II))</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td></td>
<td>concentration data from a vessel and also mounted to the MV</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sensor</td>
<td>Application</td>
<td>Parameters</td>
<td>Phase</td>
<td>Location</td>
<td>Depth</td>
<td>Data availability</td>
</tr>
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<td>----------------------------------------------</td>
<td>----------------------------------------------------------------------------</td>
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<td>-------</td>
<td>-------------------</td>
</tr>
<tr>
<td>Water samples</td>
<td>Water samples processed in laboratory off site. Samples at depth taken with Niskin, surface samples taken directly</td>
<td></td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Valeport TideMaster</td>
<td>Water level sensor deployed on edge of water body</td>
<td>Pressure (dBar)</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>WatchDog Datalogging Rain Gauge</td>
<td>Meteorological station used for rainfall only</td>
<td>Rainfall (mm/hr)</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
</tbody>
</table>

Notes

For instrumentation: Near = 0 m - 10 m from mining activity, Mid = 10 m - 50 m from mining activity, Far-field = >50 m from mining activity.

For water sampling: Near = 0 m - 50 m from mining activity, Mid = >50 m whilst still within the water body, Far-field = Outside the water body.

1 FTU/Counts to be converted to mg/l with in situ water samples.

2 Salinity is derived from the algorithms described in the UNESCO Algorithms for computation of fundamental properties of seawater. Technical Papers in Marine Science No. 44 (UNESCO, 1983).
3.1 Equipment Summary

3.1.1 Optical and Acoustic Turbidity Sensors

Fugro are well versed with using multiple methods for monitoring suspended sediments in a variety of conditions. As a result, we have developed an extensive database of calibration data. In our experience, Optical Backscatter (OBS) sensors will become unreliable once sediment values exceed 1000 mg/l. In order to provide reliable suspended sediment data as the sediment values increase, Fugro have deployed Acoustic Backscatter (ABS) sensors, in addition to OBS sensors. The acoustic measurements penetrate through the suspended sediments and return a profile through the water column at up to 2 Hz.

Due to the differing response of the OBS and ABS systems, the data are not directly comparable. For example, OBS data responds to four variables: size, shape, colour and concentration of the suspended sediment. Whilst ABS data respond to size, shape, density and concentration. These differing responses must be considered when comparing the two data types. In addition, the signal response varies due to the interaction of the wave length with the sediment size, causing OBS to respond very strongly to fine (silt size) particulates, while an ABS system at 1 MHz will respond more strongly to sand size particulates. At lower frequencies, the response becomes weaker to fine particulates.

In order to analyse datasets from the OBS sensor, data from each measurement burst are first averaged to create one record per measurement burst (for example every 10 minutes). Pre and post-deployment data are removed. The data are then visualised to establish any quality issues such as excessive rates of change (data spikes) or data gaps. Outliers and suspect data are investigated, and where possible, checked concurrently with other potential explanatory data, such as heavy rainfall or mining activity, to assist in establishing their validity. Data which do not pass quality control tests can either be flagged or replaced with null values.

The suspended sediment concentration values obtained through laboratory analysis of the water samples are used to construct a site-specific calibration. A regression is drawn up between OBS values (in FTU) and the suspended sediment concentration values (in mg/l). The equation of the best-fit line is then used to convert the OBS values into an estimate of suspended sediment concentration.

ABS data are collected when the sensor's acoustic signal is reflected back by particulate matter in the water. This raw echo intensity data can be used to extract information about the suspended sediment load in the water column. The raw amplitude (counts) values first have to be normalised to remove the effect of signal attenuation through the water and converted to a Decibel scale. Finally, the suspended sediment concentration values obtained through laboratory analysis of site specific water samples are used to construct a site-specific calibration. A regression line is drawn up between acoustic backscatter values (in normalised decibels) and the suspended sediment concentration values (in mg/l). The equation of the best-fit line is then used to convert the acoustic backscatter values into an estimate of suspended sediment concentration.

The following ABS and OBS instruments were selected for their proven track records of reliable performance during long term Fugro deployments in harsh coastal conditions.
3.1.1.1 Aquatec AQUAlogger
The Aquatec AQUAlogger (hereinafter referred to as the Aqualogger) is a compact, self-contained, data recorder with an on-board Seapoint turbidity meter for the measurement of optical backscatter (OBS). The collected OBS measurements are used as a proxy for turbidity measurement. Turbidity values are recorded over four automatically switched gain ranges, ensuring excellent resolution over the whole measurement range. Turbidity is recorded in Formazine Turbidity Units (FTU), which will be converted to estimates of suspended sediment concentration through the collection of local water samples. Fugro maintains an extensive data bank of calibrated turbidity data, which is used to strengthen the analysis of data where necessary.

Figure 3.1: Aquatec AQUAlogger OBS.

Two series of the units were used, the Aqualogger 210 and 310. They are very similar but the Aqualogger 310 allows real-time output over RS232. This feature made it ideal to incorporate to the suite of sensors fitted to the mining vehicle for integration with the ¡VAMOS! virtual reality (VR) system. Aqualoggers fitted with built-in pressure and temperature sensors were selected for deployment at mine floor level at both Lee Moor and Silvermines.

3.1.1.2 RDI 1200 kHz ADCP
An RD Instruments 1200 kHz Workhorse Sentinel ADCP was selected to undertake vessel based current profiling (see Figure 3.2). The Acoustic Bottom Tracking function allows the movement of the vessel to be removed from the overall signal. Acoustic back scatter data is acquired for individual “bins” or depth cells throughout the water column. An illustration of ADCP data binning can be found in Figure 3.3. The aim when mounting the instrument is to collect data from the surface portion of the water column, whilst ensuring the measurements are not compromised through cavitation caused by bubbles.
The ADCP was integrated with a Hemisphere Vector V113 GPS compass to ensure accurate positional data and rapidly updating heading information is collected in conjunction with the current profiles.

3.1.1.3 Nortek 1 MHz Aquadopp Profiler
The Nortek Aquadopp Profiler (Aquapro) is the ADCP that was selected for installation on the MV (Figure 3.4). It also acquires backscatter data by measuring the strength of an acoustic signal which is reflected back by particulate matter in the water. The operating principles and data processing methods are as described in section 3.1.1 Optical and Acoustic Turbidity Sensors.
Data are collected for individual cells through the water column with the cell size defined according to the measurement requirements and instrument frequency. The Aquapro was chosen for MV installation as it is capable of providing real-time data via RS232 over the MV's communications network.

Figure 3.4: Nortek Aquadopp Profiler.

### 3.1.1.4 Idronaut EA89 CTD
As with the Aquatec Aqualogger units, the Idronaut EA89 CTD is fitted with a Seapoint turbidity meter, logging FTU. Further details are located in section 3.1.2.

### 3.1.2 Idronaut EA89 CTD
The Idronaut EA89 is a robust multi-parameter probe capable of collecting data at 8 Hz, logging environmental parameters, including: depth (m), temperature (°C), dissolved oxygen (% saturation and mg/l), conductivity (mS/cm), Salinity (ppt), pH and Turbidity (FTU).

The profiles collected by the Idronaut instrument consisted of multiple “casts” (upwards or downwards profiles through the water column). When processed, pre and post-deployment data are removed, and the file trimmed down to a single cast using Fugro’s bespoke profile processing tool. All casts are visualised at this stage to allow the selection of the best available cast for each profile. These trimmed and averaged files are then exported for plotting.

Fugro deployed an Idronaut EA89 Multiparameter Probe for the collection of water quality profile data at both Lee Moor and Silvermines. The Idronaut EA89 was also integrated into the VIPS for real-time trace metal concentrations as a standalone unit and also mounted to the mining vehicle.
Figure 3.5: Idronaut EA89 Multi-parameter probe.

Table 3.2: Idronaut EA89 specifications.

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Range</th>
<th>Accuracy</th>
<th>Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth (pressure)</td>
<td>0-100 dba</td>
<td>0.05%</td>
<td>0.0015%</td>
</tr>
<tr>
<td>Conductivity</td>
<td>0-70 mS/cm</td>
<td>0.007 mS/cm</td>
<td>0.001 mS/cm</td>
</tr>
<tr>
<td>Temperature</td>
<td>-1 to +50°C</td>
<td>0.005°C</td>
<td>0.0001°C</td>
</tr>
<tr>
<td>Turbidity</td>
<td>0.03-750 FTU</td>
<td>0.05-5 FTU dependent on range</td>
<td>0.005-0.5 FTU dependent on range</td>
</tr>
<tr>
<td>Dissolved oxygen</td>
<td>0 to 50 ppm / 0 to 500 % sat</td>
<td>0.1 ppm / 1%</td>
<td>0.01 ppm / 0.1 %</td>
</tr>
<tr>
<td>pH</td>
<td>0 to 14 pH</td>
<td>0.01 pH</td>
<td>0.001 pH</td>
</tr>
</tbody>
</table>
3.1.3 Idronaut VIPS

An Idronaut VIPPlus Voltammetric In-situ Profiling System (VIPS) was commissioned for the project. At the start of the ¡VAMOS! trial, this was the only existing instrument capable of trace compound analysis at variable depth.

The VIPPlus allows measurement of Cu(II), Pb(II), Cd(II) and Zn(II) with a sensitivity of 100 pM and Mn(II) with a sensitivity of 100 nM. It permits metal speciation, i.e. it specifically determines the “truly dissolved” fraction of the trace metals (i.e. mobile metal species smaller than a few nanometres), directly in situ, without any sample handling, thus minimizing methodological artefacts. Additional determination of the total metal concentration permits calculation of the colloidal and particulate metal fraction by difference. This distinction is important for understanding the role and the fate of trace elements in a given aquatic system. Indeed, the dissolved fraction corresponds to the fraction easily assimilated by organisms while colloidal and particulate fractions play an important role in transport properties and residence time.

The VIPS system is integrated with an Idronaut Ocean Seven EA89 multi-parameter probe providing physical parameters comprising pressure, temperature, conductivity, dissolved oxygen, turbidity, redox and pH. The aim is to provide data in near real-time. This approach ensures that the information would be available to support any potential future water quality threshold requirements put in place to minimise environmental impacts of the mining activities, in situations where the mine water would be connected to the external environment.

By installing the instrumentation on the mining vehicle directly it should be possible to monitor changes in environmental parameters for all relevant activities of the mining vehicle (e.g. use of different tools, impact of track jetting, etc.).
3.1.4 Vaisala WXT520 Meteorological Station
For the collection of meteorological data at Lee Moor, Fugro installed a Vaisala WXT520 weather station. The Vaisala WXT520 is a self-contained 7-in-1 sensor, measuring wind speed and direction, gust speed, liquid precipitation, air temperature, barometric pressure and relative humidity. This device is routinely used by Fugro for long-term installation at locations, as it has proven to be highly robust and reliable.

Figure 3.7: Vaisala WXT536 meteorological sensor.

3.1.5 Valeport TideMaster fitted with Pressure Transducer
To collect water level data, Fugro installed a Valeport TideMaster Portable Water Level Recorder at both Lee Moor and Silvermines. This allowed data to be continuously collected at both Lee Moor and Silvermines, recording the change in water level through both natural and anthropogenic causes.

Figure 3.8: Valeport TideMaster Logger.
This device employs a vented strain gauge. The unit comprises a corrosion resistant, titanium-housed, vented pressure transducer, connected via a 20 m vented cable to an above water surface, battery powered logger unit. The unit is simple to install, requires minimal maintenance and allows for extended deployments.

The Valeport Tidemaster collects basic data describing the head of water above the transducer. The device was configured to collect water level data over a 40 second sampling burst at 10 minute intervals, so as to provide high resolution data whilst averaging out any wave action observed at the deployment location.

Typically, all data is logged to the device’s internal memory for download at service. However, for the Silvermines trial, the device was configured to provide a real-time output to the control cabin, to feed into the virtual environment.

Tide gauge calibrations were undertaken by means of comparison calibration dips. All data for each site was collected relative to the surface at the time of deployment. Processed data are referenced to average water level height, based on an average of the entire dataset collected.

3.1.6 WatchDog Datalogging Rain Gauge

The Spectrum WatchDog Datalogging rain gauge is a high accuracy, low maintenance tipping bucket rain collector, meeting National Weather Service (NWS) guidelines, with a 20.5cm diameter collector. The device was selected for Silvermines, over the previously used Vaisala, due to the lower power requirements and cost, due to the concerns over third party interference.

Figure 3.9: WatchDog Data Logging Rain Gauge.
3.1.7 Water sampling
For the collection of water samples at depth, Fugro used a Niskin Bottle. This device is a 5 litre, non-metallic, free-flushing water sampler featuring a spring closure. This mechanism allows water samples to be reliably collected from any depth in the water column with minimal contamination.

![Figure 3.10: Niskin bottle.](image)

The sampler is typically attached to a weighted wire rope to facilitate vertical transit through the water column. The device can be lowered through the water column either mechanically or by hand with the deployment wire marked at pre-set depth intervals so as to ensure that water samples are taken from the relevant depths. In the case of near seabed samples, care was taken to ensure the sampler does not rest on the seabed so as not to disturb sediments, thus contaminating the sample.

Surface water samples were collected directly into sterilised bottles. Where necessary, sterile syringes were used. All samples were delivered or couriered to laboratories as quickly as practicable. TSS for OBS and ABS calibration were processed by Fugro’s Portchester Laboratory. All Chemical analysis was undertaken by the United Kingdom National Laboratory Service (NLS) in Exeter.

3.1.7.1 Total Suspended Sediment (TSS)
Analysis was undertaken within Fugro, in accordance with FGBML in-house procedures based on HMSO Methods 1980 and BS EN 872: 2005. A measured volume of sample is filtered through a pre-weighed Whatman type GF/C glass-fibre filter paper with a particle size retention of 1.2 µm, which is subsequently re-dried for a specific time (1 hour) and temperature (105 ±5°C). The filter paper is then re-weighed and the increase in weight represents the total suspended solids. This method is UKAS accredited for the analysis of saline and freshwater matrices.
3.1.7.2 Chemical
The United Kingdom NLS was selected to process all non-TSS water samples, due to the wide range of UKAS accredited testing they are able to provide. The methods employed were accredited to ISO/IEC 17025.

Several samples processed were under the Minimum Reporting Value (MRV), a minimum concentration selected for reporting purposes (i.e. the less than value), which is higher than the statistically derived method limit of detection. This provides consistency of reporting as well as an allowance for sample variation. To allow data to be plotted and compared, these MRV values have been identified as ‘no result’. NLS laboratory analysis methods provide all water sample turbidity measurements in Nephelometric Turbidity Units (NTU).

3.2 Application Summary
This section details how the approach and equipment were employed at each of the trial sites. Basic configuration details and parameter selection are also discussed.

Instrumentation sampling rates and intervals were based on a compromise between battery utilisation, instrument memory and planned servicing. Data were typically collected every 10 minutes at each trial. Where possible (MV real-time data applications) the sampling rate was increased to allow increased temporal resolution.

3.2.1 Transecting
Transecting with a 1200 kHz RDI ADCP was undertaken at Lee Moor only. The frequency was selected as a good compromise between range, resolution and the ability to determine suspended sediment load. The expected 60m water depth at Silvermines dictated that a lower frequency instrument would be required, e.g typical range of a 600 kHz instrument is 50m rather than 12m for the 1200 kHz unit. These instruments are less capable of determining sediment load so the approach was modified, instead choosing to mount a Nortek Aquapro directly to the mining vehicle to provide real-time data.

A depth cell size of 0.25 m was selected for Lee Moor, with a blanking distance of 0.30 m. Transecting was undertaken at approximately 1 m/s.

During the baseline survey, transects were undertaken in north-south and east-west orientation. Once the LARV anchors were in place, it was necessary to run all transects along the anchor wires instead, the turn of each transect being as close as possible to the LARV, mining vehicle and potential plume from the mining vehicle. The transects are highlighted by the yellow dashed line in Figure 3.11. Images and screenshots taken whilst transecting are presented in Figure 3.12 to Figure 3.14.
Figure 3.11: Lee Moor site plan showing in-pit and below-pit sampling locations.

Figure 3.12: 1) ADCP and Hemisphere Vector ready for transecting, 2) Surveyor monitoring backscatter output during transecting.
Figure 3.13: Baseline transect (07/09/2017) screenshot taken, showing backscatter in dB from each transducer, displaying clear stratification, in particular at ~9 m.

Figure 3.14: Screenshot taken whilst mining (10/10/2017), showing backscatter in dB from each transducer, displaying clear stratification, in particular at ~9 m. Transect runs from right to left, starting at the shore adjacent to outfall, running to the MV (centre of transect) to shore along anchor cable.
Whilst Figure 3.14 shows clear stratification in the water column, it is interesting to note that there are some areas where strong mixing occurs. High turbidity flow is evident on the right side of the transect, with material apparently flowing across the mine at lower levels.

3.2.2 Fixed

3.2.2.1 Bed (Mine Floor)

For both trial sites, bespoke lightweight frames were deployed, housing different instrumentation at each site. The sensor selection was based on the expected conditions, and in the case of Silvermines, from lessons learnt at Lee Moor.

At Lee Moor, two frames were deployed on L-shaped moorings (see Figure 3.15). Each frame housed a Nortek Aquapro, an Aquatec Aqualogger 210 and a diver locator beacon. The frames were deployed approximately 75 m and 150 m away from the LARV and mining vehicle, marked by L1 and L2 in Figure 3.11).

For the project, the Aquapro was configured with 40 x 0.5 m bins, a good compromise between high resolution data collection and range. The measurement regime was modified throughout the trials, to best suit the project phase and location.

The Aqualoggers proved themselves to be reliable for the site. Figure 3.16 shows the turbidity levels of both mid and far-field Aqualoggers at Lee Moor.

![Figure 3.15: 1) Survey vessel with 2 instrument frames following recovery at Lee Moor, 2) Close up of instrument frame at Lee Moor, housing Nortek Aquapro, Aquatec Aqualogger and diver locator beacon.](image)

With a maximum range of up to 25 m, the Nortek Aquapro’s were not suitable for the 60 m depths expected at Silvermines. As explained in D5.5, there was also the risk of similar stratification experienced at Lee Moor, causing calibration issues for the data. Instead, two Aquatec Aqualoggers were deployed on frames with straight line moorings (see Figure 3.17). These were positioned as close to the 2 planned mining locations (Site A and B) at Silvermines as possible, allowing for mid and far-field
measurements to be taken throughout the trial. The actual deployment locations are referred to as L1 (Site A) and L2 (Site B).

Data for both sites were downloaded at intervals throughout the trial.

Figure 3.16: Time series plot showing, in order (top to bottom) bed temperature and rainfall, water level, Aqualogger converted turbidity and MV activity at Lee Moor.

Figure 3.17: 1) Close up of Aquapro mounted to equipment frame at Silvermines, 2) Two instrument frames and moorings ready for deployment.
3.2.2.2 Surface
No instrumentation was surface mounted at Lee Moor. At Silvermines two Aqualoggers were mounted immediately beneath the surface floats for the bed mounted instrumentation (see Figure 3.17). As with the bed mounted instrumentation, these were located at L1 and L2.

Data were downloaded at intervals throughout the trial.

3.2.2.3 Water Level Recorder
On each site, the pressure sensor was fixed in position, in a location which was unlikely to be affected by other works on site. To allow accurate measurement, the transducer needs to be fixed, preventing movement, at a depth which ensures that it will not dry out.

Due to the lack of sheer walls at Lee Moor, it was necessary to install the Valeport Tidemaster on a scaffold frame, piled into the clay bed, in a location away from potential interference (see Figure 3.18).

![Figure 3.18: Lee Moor Valeport Tidemaster logging unit and transducer, secured to scaffold pole prior to installation, 2: Lee Moor Valeport Tidemaster following installation.](image)

Following a request by the Partners for real-time water level data at Silvermines, the decision was made to locate the Valeport Tidemaster as close as possible to the control cabin, connected via a 50 m data cable. The transducer was attached to a weighted stainless steel strop and anchored in place by drilling a U-bolt into the vertical face of a nearby area of rock, securing it in place with a chemical anchor.

In October, both the logger and transducer were moved to a new location, following a move of the control cabin, to increase the range of the umbilical. The transducer was relocated 0.30 m deeper. This offset was applied to the data in post-processing.

Water level data for both sites were downloaded at intervals throughout the trials.
3.2.2.4 Rainfall sensor

A Vaisala WXT 520 meteorological station was installed on top of the SMD workshop container at Lee Moor. The height of the meteorological station was approximately 4 m above ground level (Figure 3.20). The Vaisala was used for an indication of rainfall only.

A data logging rain bucket was installed at Silvermines, adjacent to the welfare facilities. The rain bucket was fitted to a scaffolding pole which had been piled into the ground (Figure 3.21). Data for both meteorological sensors were downloaded at intervals throughout the trial.
3.2.3  Mining Vehicle Mounted Instrumentation

This section outlines the installation of sensors installed on the MV for collection and telemetry of real-time data. In all instances, data were also logged internally.

For trace metal concentrations, an Idronaut VIPS with integrated EA89, was installed at both Lee Moor (Figure 3.22) and Silvermines (Figure 3.23). The instrument had limited success; at Lee Moor, once mining commenced and the water became well mixed, the levels of dissolved oxygen were too high to permit sampling without damage to the sensor; at Silvermines, the vibrations damaged the instrument beyond economic repair. An example plot of the VIPS data from Lee Moor is presented in Figure 3.24.

Despite the damage to the Idronaut VIPS, the EA89 multi-parameter probe integrated to the VIPS, proved successful at collecting data whilst mining (Figure 3.25).

Both Idronaut sensors were mounted to the rear of the MV, on the opposite side to the cutter head. EA89 data was output at 1 Hz. VIPS measurements were to be undertaken on request by the user, each measurement taking approximately 45 minutes and requiring the sensor to be deployed at depth, where the dissolved oxygen levels were under 10%.
Figure 3.22: Idronaut VIPS and EA89 probe mounted to mining vehicle at Lee Moor.

Figure 3.23: Idronaut VIPS and EA89 probe mounted to mining vehicle at Silvermines.

Figure 3.24: Example VIPS data, presenting trace heavy metal concentrations at Lee Moor.
Figure 3.25: Example data from 25/10/2017 at Lee Moor; from top down, Idronaut depth and temperature alongside rainfall and temperature at L1 and L2, Idronaut OBS data from MV alongside Aqualogger OBS data from L1 and L2, MV activity. Time series plot shows significantly higher turbidity levels logged at the mining vehicle whilst mining, decreasing with distance.

At Silvermines, Fugro integrated a 1 MHz Nortek Aquapro (Figure 3.26) for ABS turbidity data throughout the water column at a range of 20 m, and also an Aquatec Aqualogger, for OBS measurement adjacent to the vehicle (Figure 3.27). The sampling regime was modified throughout the trial to optimise sampling. Both instruments successfully sent data in real-time, allowing integration with the ¡VAMOS! VR system.

To allow for real-time suspended sediment data, an approximated calibration was applied to both the Aquapro and Aqualogger, allowing turbidity in counts and FTU to be converted into estimates of concentration in mg/l. The calibration for both instruments were finalised following post processing at the end of the trial, once all TSS samples had been processed.
3.2.4 Water Sampling

Water sampling was undertaken at both Lee Moor and Silvermines. TSS samples were taken for sensor calibration, primarily for the fixed Aqualoggers. Samples were also taken for chemical analysis, dependant on historical data available to the consortium prior to the trials taking place.

For TSS both at Lee Moor and Silvermines, 1 hour of water sampling was undertaken at repeated visits throughout each trial. Each hour allowed for a water sample to be taken during each of the 6 Aqualogger measurements that hour.
Water samples for chemical analysis from Lee Moor were taken from the centre point of the water body, shown as location WS in Figure 3.11. Samples were also taken by the South bank of Whitehill Yeo Pit South Pool (shown in Figure 3.29, and referred to as Location X1 in D5.5) and the Y-Launder (referred to as Y1). Whitehill Yeo Pit South Pool is connected via a small stream running from the main Lee Moor pit for the trial. The Y-Launder is an existing monitoring point for the mine owners, located before their processing facilities. These sampling locations allow for any potential leakage from the site and chemical changes to the water body to be monitored.

The parameters for Lee Moor were based on the existing list of parameters monitored by IMERYS, the mine owners, with additional samples taken to support the output from the Idronaut VIPS.
Figure 3.29: Whitehill Yeo Pit South pool, showing outlet gate on South bank.

Figure 3.30: Water sampling underway at Y-Launder.
Figure 3.31: Silvermines water sampling locations, provided by Golder Associates Ireland.
The Silvermines site (Magcobar) required a more thorough approach to chemical sampling, to help ensure that any potential releases into the environment were monitored. Multiple entry points and pathways were identified to and from the water body (see Figure 3.31). These, along with the pit monitoring locations, are summarised as follows:

- L1 – Instrumentation location at Site A (Figure 3.32);
- L2 – Instrumentation location at Site B;
- PW-UGW – Underground pit workings leading to Knight Shaft release point;
- PW-K – Karst formation, potentially allowing water movement through rocks to nearby stream;
- ABV-PIT – Concrete channel above pit, diverting water away from Magcobar;
- SW7-EPA – Historical sampling point, downstream of potential PW-K release point;
- BLW-PIT – Lower end of concrete channel which diverts water flow around Magcobar; fly-tipping evident with several hundred tyres present (see Figure 3.33);
- SW3-MAG-GA – Lower end of waterfall, before entering Magcobar;
- SW12-GAR – Historical sampling point, used when Knight Shaft is dry.

Additional samples were taken at the dewatering plant input and output, for inter-comparison, for an indication of the dewatering plant’s effectiveness (Figure 3.34).

The chemical water quality parameters selected for Silvermines were based upon the Final Report of Expert Group for Silvermines County Tipperary, Lead and Other Relevant Metals, produced by the Environmental Protection Agency (EPA, 2004). The report focused on trace heavy metals of concern for the area: lead, cadmium, arsenic, zinc, copper and mercury. The report also outlines what were deemed at the time to be the relevant thresholds for surface water abstraction, based on European Communities (Quality of Surface Water Intended for the Abstraction of Drinking Water) Regulations, 1989 S.I. No. 294/1989). Though now defunct after the introduction of the Water Framework Directive, they provide a useful visual aid for the results presented in D5.5. The threshold limit selected for comparison is the Category A3 Surface Water Quality Standard, for waters requiring the greatest amount of work to transform them into drinking water, requiring intensive physical and chemical treatment, extended treatment and disinfection (Figure 3.35 shows lead concentrations at Silvermines against these threshold limits).

The ¡VAMOS! below pit water sampling locations shown in Figure 3.31 include historical long term water sampling locations in the surrounding area that are surveyed by the EPA. This allowed some comparisons with historical data. It should be noted that elevated heavy metal concentrations were observed at the EPA's Knight Shaft alternative sampling point SW12-GAR (Figure 3.35). This sampling point is installed at a local industrial site where trucks and agricultural machinery is being serviced.

Engine or transmission oils had clearly been poured into drains by the SW12-GAR sampling point. These elevated levels are not caused by ¡VAMOS! mining activities. This is also made clear in D5.5 Proof of Environmental Viability of the Submerged Mining Concept. However, that fact that these differences can be discriminated and attributed to difference sources demonstrates the effectiveness of the monitoring approach and techniques.
Figure 3.32: 1) Recovery of Niskin bottle at Silvermines, 2) Completed set of water samples at L1.

Figure 3.33: BLW-PIT sampling point.
Figure 3.34: Water sampling at Silvermines dewatering plant.

Figure 3.35: Silvermines total lead concentration (ug/l) throughout the trial; high concentrations visible at SW12-GAR throughout.
4 Real-time Environmental Data Broadcast and Visualisation

Fugro developed and demonstrated pioneering real-time environmental data acquisition technology that was successfully integrated with the INESC Positioning, Navigation and Awareness System (PNAS) during the Silvermines trials. The environmental data were broadcast via the PNAS Robot Operating System (ROS) protocols to the BMT virtual reality (VR) environment for real-time visualisation. This technology could successfully be deployed to future submerged mining projects to enable real-time environmental monitoring, mine licence compliance, and adaptive management of mine plans.

4.1 Environmental Sensor Selection Approach

Decades of academic research and industrial application of aquatic and marine sensors have demonstrated that the efficacy of data acquisition and subsequent usefulness of datasets are affected and constrained by many factors. The most significant factors include:

- The robustness of sensors.
- The measurement sensitivity of sensors.
- The reliable ranges of operational parameters.
- Underlying deployment assumptions and pre-deployment calibration requirements.
- Post-processing requirements.

Given the compressed mining trial programme and budgetary constraints, the approach to sensor selection adopted at the bid stage was to utilise existing sensor technology with well-understood data acquisition capabilities, rather than to develop new sensors. Therefore, ¡VAMOS! research and assessment effort has focussed on how best to deploy existing commercial off-the-shelf (COTS) sensors and how to adapt acquisition and processing techniques in the most appropriate ways for submerged mining.

As the mining depths and geological conditions encountered at Lee Moor were different to the sites appraised at bid stage, it was determined that the Lee Moor trial would serve as proving ground for sensor performance, before determining an appropriate system of sensors and data processing for real-time data broadcast during the Silvermines trial.

4.1.1 Environmental Sensors Selected

The following sensors successfully provided real-time data during the mining trials. Table 3.1 provides the details of the environmental parameters acquired and logged during the trials.

MV mounted:
- Aqualogger 310
- Nortek Aquapro 1 MHz ABS
- Idronaut EA89 Multiparameter Probe
- Idronaut VIPS

Shore deployed:
- Valeport TideMaster
Vessel deployed:

- RDI 1200 kHz ADCP

The vessel deployed RDI ADCP sent data in real-time to a laptop on the vessel, but was not integrated to the Mining Supervision System (MSS) Human Machine Interface (HMI).

### 4.1.2 Voltammetric In-situ Profiling Systems

The Idronaut VIPS has the potential to provide real-time dissolved metal data when integrated with the Idronaut EA89 Multiparameter Probe. As such, it was an instrument that was of great relevance to the monitoring objectives of the ¡VAMOS! project. Fugro successfully cabled and integrated the instrument on the MV, and demonstrated data transmission.

However, the technology was initially designed for long-term static monitoring of deep fresh water environments such as lakes. As such, the sensors are fragile and have a narrow operating envelope of dissolved oxygen (DO) concentrations. Therefore, Fugro explicitly consulted Idronaut on the application of this novel technology to submerged mining, and Idronaut stated that the instrument would operate under the ¡VAMOS! trial conditions prior to equipment purchase.

The operating depth at Lee Moor was shallower than expected trial sites at bid stage, and resulted in one of the VIPS sensors being destroyed, as a result of higher DO concentrations encountered at this site. After this experience, it was decided that no further VIPS deployments should be carried out until deeper mining could be conducted at the second trial site.

However, the second trial site (Silvermines) was comprised of ore deposits with rock strengths of approximately 200 MPa – considerably harder than the design specification of the MV. Therefore, the MV experienced extreme levels of vibration - greater than 10 g (the maximum g-force that the Inertial Navigation System (INS) accelerometers could record). As a result, the VIPS internal circuitry was irreparably damaged during the Silvermines trial.

Despite the harsh mining trial conditions exceeding the VIPS operational robustness, the dissolved metal concentration measurement of the VIPS system remains a technology of interest to submerged mining. However, Fugro's experience of the technology under submerged mining conditions indicates that considerable effort would need to be expended to provide the level of calibration that would support reliable data acquisition. The intrinsic nature of the VIPS sampling and processing technology requires the deployment platform to be submerged for long periods. VIPS data points would generally be produced at one-hourly intervals. Any mining concept that required repeated retrieval of the MV above the water is liable to harm the sensors and preclude reliable data acquisition.

### 4.1.3 Mine Floor Instrumentation

The mine floor (bed) instrumentation was not cabled through to the FEDPC due to the requirement to frequently relocate the bed frames relative to the mining location. However, the successful broadcast of real-time data from the MV-mounted sensors demonstrates that real-time monitoring from mine floor locations is possible.
Should cabled mine floor sensors be required for future submerged mining projects, mine planning and management would need to consider sensor cable locations, in order to prevent cable entanglement or severance. Acoustic modems could be considered for future submerged mining projects, however acoustically noisy pit water environments may limit the effectiveness of aquatic acoustic modems. Another alternative would be to use buoys with real-time over-the-air communications such as WiFi or mobile cellular networks.

4.2 Robot Operating System Integration

Fugro installed a dedicated Microsoft Windows 7 PC in the control cabin (CC) to receive and process real-time environmental data. The MV mounted instruments were all cabled through the MV’s junction box (JB) and MV umbilical through to rack 2 in the CC, and on to the Fugro Environmental Data PC (FEDPC). Pit water level data from the Valeport TideMaster was directly cabled to the FEDPC. All real-time sensor data was transmitted over RS232.

An Ubuntu 16.04.5 LTS virtual machine (VM) was installed on the FEDPC (via Oracle VirtualBox) to host the ROS Kinetic distribution that would broadcast environmental data to the MSS and the HMI, hereinafter referred to as the VR environment.

The FEDPC and Fugro ROS VM were assigned static IP addresses and defined usernames for the ROS Master server managed by INESC. Fugro developed Windows and Linux client software that interfaced with the data delivered by the Aqualogger 310, Nortek Aquapro 1 MHz ABS and the Valeport TideMaster, and broadcast these data across the ROS network via ROS publisher/subscriber protocols. These environmental data were successfully broadcast to the real-time VR environment.

Each real-time sensor had a dedicated and specific ROS node initialized for data broadcast, allowing sensors and nodes to be taken offline, if necessary, without affecting data transmission for the other sensors. Each sensor had specific ROS message formats defined and compiled on the Fugro ROS VM and on the INESC ROS Master server. Figure 4.1 shows a screenshot of the ROS Node Manager displaying Fugro nodes running simultaneously on the Fugro test PC.
Figure 4.1: Fugro sensor ROS nodes running concurrently within the Ubuntu guest VM on the Fugro test PC.

The Node Manager in Figure 4.1 is also displaying a pop-up window echoing test message data in real-time for the Aqualogger ROS topic. The pop-up window shows the fields of the ROS messages broadcast for the Aqualogger sensor.

4.2.1 The Virtualised Architecture Approach

The real-time capable sensors deployed required configuration and communications software that is Windows-based. In addition, some of Fugro's proprietary real-time processing software is also supported on Windows only. However, stable ROS distributions are only supported on Linux.

Therefore, the environmental data transmission and broadcast pathway would have to include both Windows and Linux operating system (OS) components. Two dual-OS architectural approaches for ROS data broadcast were considered, developed and tested prior to final deployment:

- ROS installation on Windows Subsystem for Linux (WSL) on a Windows PC.
- ROS installation within an Ubuntu Linux guest VM on a Windows PC.

Whilst these architectural approaches were specific to the ¡VAMOS! EMS, the lessons learned could prove useful to other systems that require the integration of multiple OS components to ROS systems.
4.2.1.1 Windows Subsystem for Linux

WSL is a compatibility layer that runs natively on Windows. Early development of the real-time system focussed on WSL deployment as there were a number of potential advantages that were of interest:

- Lower overall system resource (memory and CPU) footprint.
- Ability to execute native Windows applications from within the WSL environment, potentially allowing increased levels of overall system automation.
- Reduced system configuration requirements, particularly for file system management and network configuration.

One drawback of the WSL approach was that it does not provide a native windowing environment for Linux GUIs. However, this was solved by installing VcXsrv to provide a Windows X-server for Linux executables installed on WSL.

A ROS Kinetic distribution was successfully installed to a WSL environment, and core ROS functionality was successfully tested. However, testing revealed a number of problems with WSL ROS installations that presented a risk to production deployment. Two issues in particular proved very problematic. Firstly, WSL did not (at the time) support IP multicasting, which would have precluded the option of multi-master ROS architecture, should on-site integration have found it would be required.

Secondly, and more troublesome was the fact that the ROS WSL environment regularly developed initialisation states that caused permanent boot time abortion with hexadecimal error messages that provided no useful information about the source of the issue. In some cases, this appeared to be caused by internal Linux symbolic file and directory links that are required by the ROS installation. This initialisation problem could be solved by deleting WSL cache files. However, in other cases the only solution was to completely reinstall the WSL system, the ROS installation, and the Fugro real-time system. This is a lengthy process, causing monitoring down-time, and introducing the risk of configuration errors.

In the light of these fundamental problems, system unreliability and drawbacks, Fugro determined that WSL deployment for real-time ROS integration was not an acceptably reliable architectural solution, and WSL ROS development was abandoned.

4.2.1.2 Linux Virtual Machines

The final production real-time EMS was deployed via a VM. The VM solution provided a number of inherent advantages over the WSL approach that could be useful to other multi-OS submerged mining data acquisition concepts, not just environmental monitoring.

1. Once a stable ROS VM has been created, it is relatively simple to copy the entire VM to another compatible physical device as a virtual disk image (VDI), and to operate successfully.
2. In most instances, deployment to new devices only requires straight-forward configuration of network interfaces on the new host system.
3. It facilitates easy and reliable testing of ROS message publishing and subscribing across multiple ROS hosts.
4. In separated test and production systems, code improvements can be tested in functionally-identical
test environments before being securely copied to production systems, providing confidence in the
reliability of code deployed to production environments.

5. Reliable, production-hardened VMs can be rapidly deployed to other mining projects with minimal
setup overheads.

Whilst the VM approach was successful, there is an additional system resource overhead in running the
VM that may be worth considering for potential future submerged mining deployments. Should
multi-OS ROS installations be necessary for deployment with submerged pressurized, battery-powered
instrumentation, it will be vital that the systems are small and energy efficient. Although not tested
during the ¡VAMOS! trials, it should be possible to deploy VMs on small, integrated single-board
computer (SBC) solutions.

The ¡VAMOS! trials showed that the entire simultaneous multi-node ROS Ubuntu 16.04 LTS desktop
VM consumed around 1.2 GB of RAM. Testing of other Ubuntu-based desktop distributions, such as
Kubuntu 18.04 have lower memory requirements. This memory footprint could be substantially
lowered in a non-desktop Linux installation, and should therefore be within the capabilities of modern
SBCs.

4.2.2 Data Selection for Broadcast and Visualisation

Not all environmental sensor data acquired and broadcast data were visualised in the VR environment
during the Silvermines trial. Whilst all sensor data received were successfully broadcast across the ROS
network, providing all sensor data to the HMI would have overcrowded the screen real estate. Therefore,
only a subset of the real-time environmental ROS data was visualised as a demonstration of
technological proof of concept. Figure 4.2 displays an example of Nortek Aquapro ABS turbidity data
broadcast over the ROS network to the VR environment for visualisation purposes.
4.2.3 On-site Input/Output Issues

The complex multi-component nature of the ¡VAMOS! hardware-software network interfaces required occasional rebooting of networked servers in the data pathway. In practice this led to intermittent data delivery and to occasionally corrupted records.

The VM deployment approach allowed environmental data to be processed by an offline test system that allowed on-site code improvements that could be tested before deployment to the live production system. This facilitated on-site code development that increased fault-tolerance to Input/Output (I/O) related issues, resulting in demonstrably production-hardened solutions for real-time environmental monitoring.
5 Conclusions

A comprehensive range of environmental monitoring technologies and approaches was successfully trialed and evaluated to assess their usefulness and effectiveness for supporting environmental impact assessment of future inland submerged mining projects. The trial results demonstrate that existing technologies and techniques are capable of supporting the EIA process, including real-time monitoring for important environmental parameters.

Whilst the harsh mining trial conditions exceeding the VIPS operational robustness, the dissolved metal concentration measurement of the VIPS system remains a technology of interest to submerged mining. However, it is possible that engineering solutions could overcome some the inherent fragility of the sensors and their analytical processes for submerged mining applications.

Recommendations for improvements to the full data pipeline for EIA purposes, including parameter selection, requisite sensor performance envelopes and deployment approaches are provided in D6.3 Environmental Impact Assessment. Potential applications to marine mining are also included, where relevant.
6 References
