

# ISPRS Education and Capacity Building Initiatives 2024

## POSER: An Open-Source Simulation Platform for Teaching and Training Underwater Photogrammetry

### SCIENTIFIC AND TECHNICAL REPORT ON PROJECT ACTIVITIES

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#### 1. Background, Technical Context, and Educational Motivation

Underwater photogrammetry has become a fundamental technique for three-dimensional documentation and measurement across multiple application domains, including marine exploration and mapping, offshore industry and metrology, coastal and civil engineering, underwater archaeology, and marine ecology. Despite its increasing adoption, achieving accurate 3D measurements underwater remains significantly more complex than in terrestrial photogrammetry.

The primary challenges arise from the distinct physical properties of the underwater environment, which fundamentally alter image formation and light propagation.

##### 1.1. Housing and Mechanical Constraints

Due to the high electrical conductivity of water, imaging sensors and electronic components must be enclosed within waterproof housings equipped with optically transparent interfaces, typically flat or hemispherical (dome) ports. These interfaces introduce refractive effects that modify the geometric projection model of the camera, potentially generating optical aberrations and distance-dependent geometric distortions.

Additionally, the density of water—approximately 800 times greater than air—leads to substantial hydrostatic pressure acting on the housing structure. As depth increases, the enclosure must withstand significant mechanical stress, meaning that structural requirements often influence optical design. Consequently, camera housing geometry is governed not only by optical performance but also by mechanical resistance to pressure.

## **1.2. Refractive Effects and Optical Variability**

The refractive index of water varies with temperature, salinity, pressure, and wavelength. This variability affects the bending of light rays at the air–glass–water interfaces and can invalidate the central projection assumption commonly adopted in standard photogrammetric models. As a result, imaging systems must often be calibrated under specific environmental conditions to ensure geometric accuracy.

Failure to properly model refractive effects may lead to systematic errors in bundle adjustment, depth-dependent distortions, and scale inconsistencies in reconstructed 3D models.

## **1.3. Light Attenuation, Scattering, and Spectral Effects**

Water is an optical medium containing suspended organic and inorganic particles such as phytoplankton, sediments, and pollutants. These particles cause:

- Forward scattering and backscatter (image blur, reduced sharpness, contrast degradation, and additive noise)
- Wavelength-dependent absorption (color shifts and loss of spectral balance).

Light attenuation increases with depth and with the distance between the camera, the object, and any artificial light sources. Longer wavelengths (e.g., red light) are absorbed more rapidly than shorter wavelengths, producing characteristic bluish or greenish color dominance in underwater imagery.

## **1.4. Illumination and Surface Conditions**

The quantity and quality of light penetrating the water column depend on solar elevation, geographic location, season, and sea state. Surface conditions play a crucial role:

- Calm water can behave as a reflective mirror surface.
- Rough seas increase absorption and reduce light transmission.
- Wavy surfaces refract incoming rays, producing dynamic bright patterns known as “caustics”.

Caustics generate spatially varying illumination patterns that complicate automated 2D feature extraction and matching and degrade texture quality in photogrammetric reconstructions. Their intensity depends on sun elevation, turbidity, and depth, typically diminishing after a few meters below the surface.

### **1.5. State of the Art and Educational Gap**

A broad technical literature exists on the physical properties of water and their influence on underwater image formation (Morel, 1974; Jaffe, 1990; Bryson et al., 2013). These works provide detailed theoretical and experimental analyses of light propagation, optical attenuation, and refractive modelling.

However, while scientifically rigorous, such resources can be overwhelming for newcomers and practitioners with limited backgrounds in optical physics, radiative transfer theory, or photogrammetric modelling. The gap between theoretical descriptions and practical survey implementation remains substantial.

For these reasons, novel teaching paradigms are increasingly required. Emerging approaches leverage advanced digital technologies such as:

- Computer-based simulations.
- Augmented and virtual reality.
- Interactive visualization tools.
- Game-based learning methodologies.

These approaches aim to make complex physical principles more intuitive and experimentally accessible.

### **1.6. Role and Potential of Simulation Platforms**

In recent years, the potential of simulation platforms has become evident both in research contexts (e.g., Nakath et al., 2022; Zwiilmeyer et al., 2021; Wang et al., 2019) and in educational environments (e.g., Luhmann et al., 2022). Simulation environments offer several advantages:

- Reproduction of environments that are difficult, costly, or dangerous to access.
- Execution of statistically significant numbers of controlled experiments.
- Reduction of operational costs.
- Systematic variation and isolation of influencing parameters.
- Availability of ground-truth geometry for quantitative validation.

Nevertheless, simulation solutions are not without limitations. Accurately modelling complex light transport, scattering phenomena, and refractive geometries remains an active area of research. Numerical approximations, computational constraints, and

model simplifications can introduce discrepancies between simulated and real-world behavior.

Despite these limitations, simulation-based approaches hold undeniable value, particularly in educational contexts and in scenarios where researchers and practitioners have limited access to field resources.

### **1.7. Motivation for POSER**

Within this context, the POSER framework was developed to provide a structured, physically informed, and pedagogically oriented 3D simulation environment specifically designed to support the teaching and learning of underwater photogrammetry. By enabling controlled and repeatable experimentation, POSER seeks to bridge the gap between theoretical optical models and practical survey design, fostering a deeper understanding of underwater imaging challenges.

## **2. Objectives and Goals of the POSER Project**

POSER is an educational simulation platform for underwater photogrammetry with the primary objective to create a controlled digital learning environment where students and practitioners can actively acquire surveying skills and understand best practices through experimentation within idealized and reproducible scenarios.

The platform enables users to isolate and systematically vary relevant parameters—such as acquisition geometry, lighting configuration, and environmental conditions—within a closed simulation framework. While the core mission is educational, the project also contributes to advancing simulation methodologies applicable to research contexts.

Developed through a cross-disciplinary collaboration that involves geomatics specialists, oceanographers, archaeologists, data analysts, and instructional designers, POSER provides a versatile empirical framework for testing and comparing standard underwater Structure-from-Motion (SfM) and Multi-View Stereo (MVS) workflows. The system supports:

- Evaluation of survey planning strategies.
- Analysis of acquisition geometry and redundancy.
- Demonstration of the effects of improper data capture.
- Communication of best practices for underwater mapping.

The simulator is implemented as a customizable, open-source digital platform, publicly available to foster community-driven and cross-disciplinary development. A key long-term goal is to contribute to the establishment of rigorous standards for underwater field data acquisition.

POSER integrates both reality-based and synthetic underwater environments to replicate common challenges encountered in survey planning and execution. Simulated experiments generate image datasets that allow users to explore fundamental imaging concepts such as ground sample distance (GSD), image overlap and side lap, and artificial illumination design. These datasets can subsequently be processed using different photogrammetric software solutions to evaluate reconstruction performance and compare achievable accuracy under varying conditions.

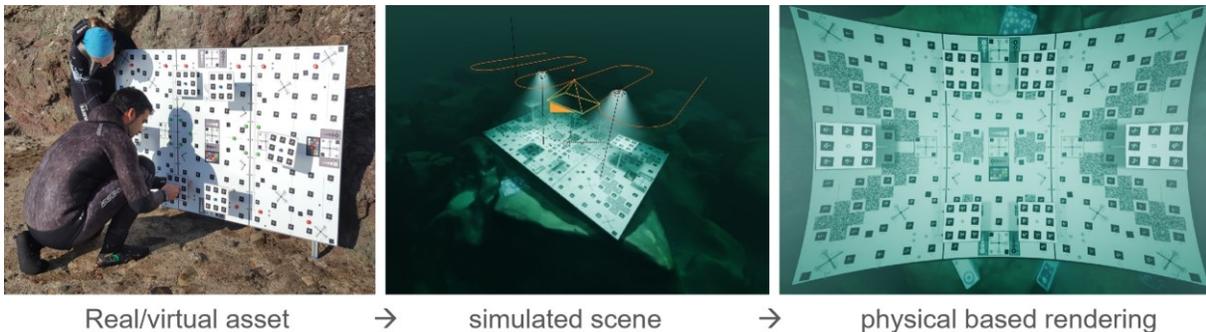


Figure 1. A calibration test-object (left, Menna et al., 2017) is virtually inserted in an underwater 3D scene in Blender (center and right) to simulate an underwater calibration of a camera enclosed in a waterproof housing mounting a flat port. The simulated images are generated using a physically based ray-tracing approach that can accurately simulate physical phenomena such as refraction, scattering, backscattering, and volumetric absorption. The resulting image (right) shows heavy pincushion radial distortions and a bluish color dominant.

The remainder of the project documentation details the simulator's main functionalities, presents preliminary results, and illustrates applications across diverse underwater domains.

### 3. The POSER Simulator in Blender

The POSER simulator builds upon a preliminary underwater simulation framework previously implemented in Blender to design and analyze camera networks commonly adopted by research institutions such as NOAA, the National Parks Service, and the Scripps Institution of Oceanography (Giuseffi 2020). The earlier prototype enabled real-time visualization of camera trajectories over a scene, with simultaneous display of the camera's local perspective. Rendered image datasets were processed using Structure-from-Motion (SfM) and Multi-View Stereo (MVS) pipelines, allowing direct comparison of resulting 3D reconstructions. POSER extends the work in Giuseffi (2020) including the developments from Nakath et al. (2022) integrating it into an educational and experimental framework for underwater photogrammetry. Hereafter a list of implemented features for educational purposes:

- POSER models dome, flat, and cylindrical ports, allowing controlled analysis of aberrations such as field curvature and astigmatism (Menna et al., 2016, 2017; Menna et al., 2020; Nocerino et al., 2021; She et al., 2022; Rofalski et al., 2022).
- Photogrammetric evaluation: Datasets include ground-truth geometry, camera poses, and intrinsic parameters for SfM/MVS reconstruction and error analysis (Figure 2).
- Parameter control: Acquisition variables (overlap, baseline, lighting, turbidity) can be isolated and systematically varied, enabling controlled experimentation.
- Educational accessibility: Custom UI panels and Python scripting simplify Blender's interface for students and practitioners.
- VR integration: Immersive visualization of scenarios supports interactive teaching and training.

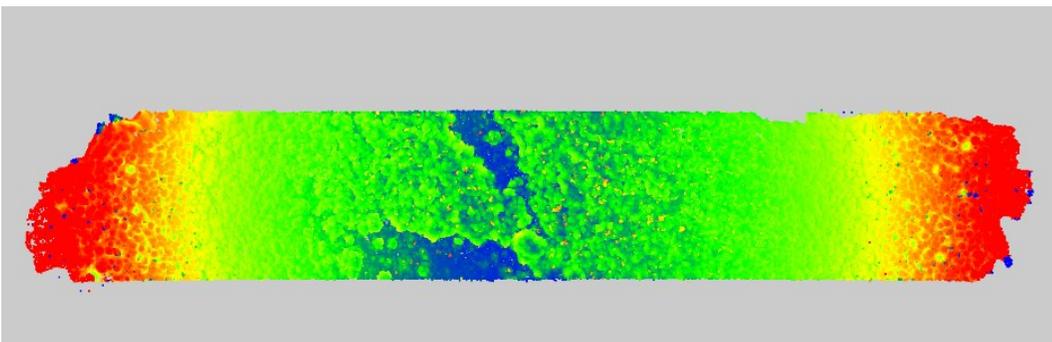
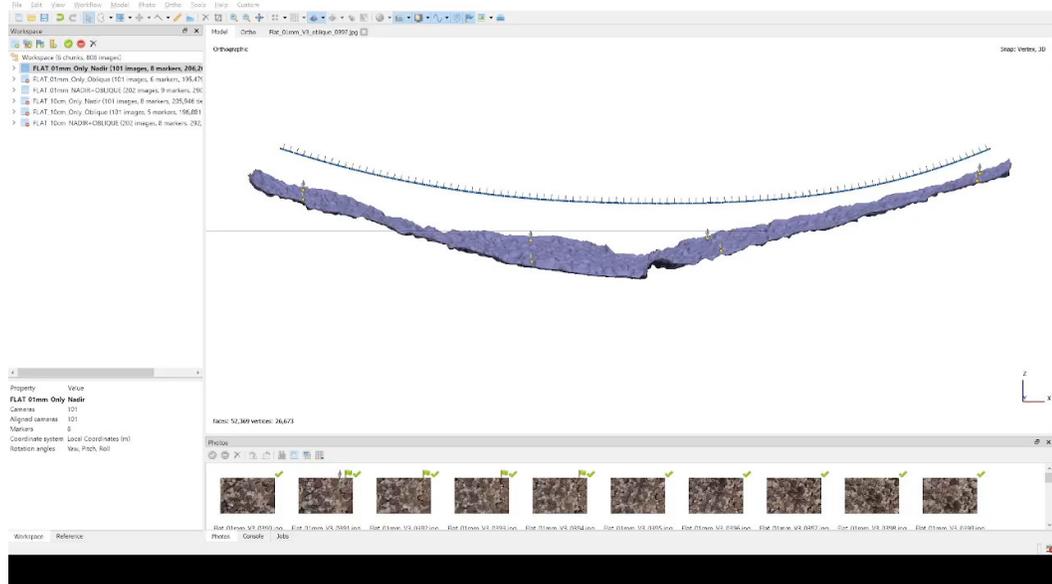


Figure 2. Example of error analysis for a simulated flat port dataset with nadir network that has been processed with non refractive SfM-MVS software (Metashape, up). The bending of the 3D model due to uncompensated systematic errors are displayed as Color-coded errors (down).

Furthermore, POSER extends the developments in Nakath et al. (2022) by introducing rigorous and flexible modelling of refractive distortions and optical aberrations, focus and depth of field for:

- centered and non-centered dome ports,
- flat ports;
- cylindrical port geometries (introduced in POSER);

enabling the investigation of:

- The formation of virtual images and focusing implications (introduced in POSER).
- Field curvature (associated with dome ports - introduced in POSER).
- Astigmatism (commonly linked to flat ports - introduced in POSER).
- Depth-dependent geometric distortions.
- Deviations from the central projection assumption.

These capabilities allow users to assess the impact of improper optical modelling and calibration strategies on 3D reconstruction accuracy (Figure 3 and 4).

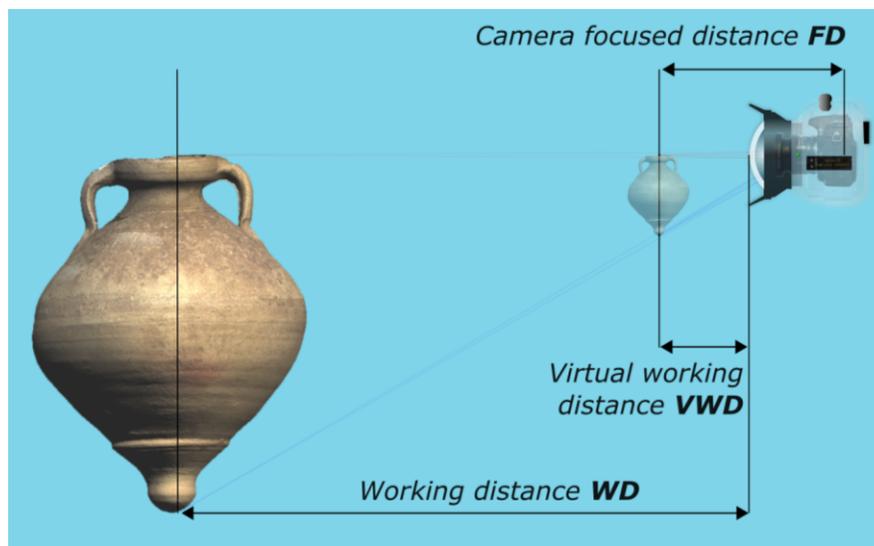
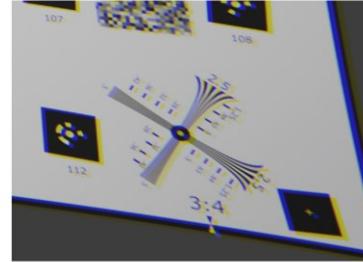
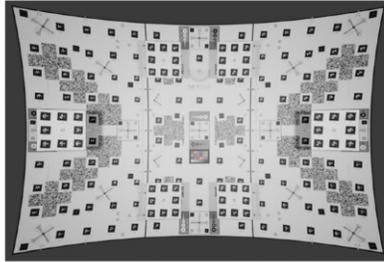
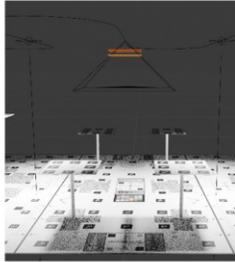


Figure 3. Illustration from Menna et al.(2016) showing the virtual image formation in a dome port.

### Flat port



**Flat  
(EP off the  
planar  
surface)**



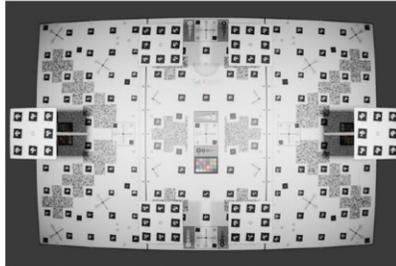
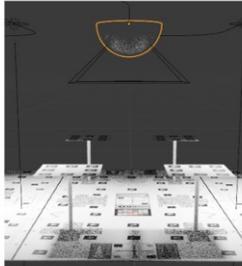
Camera-to-object distance 1.3m, EP 3cm from the inner surface of the flat.  
Flat thickness of about 15mm

Corner blur due to astigmatism. Strong chromatic aberrations visible.

### Dome port



**Dome  
(EP  
uncentered  
Backward)**



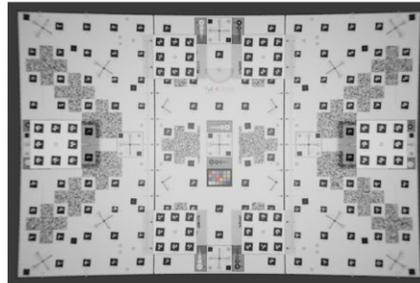
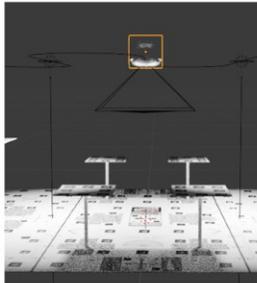
Camera-to-object distance 0.75m. EP backward longitudinal misalignment 5cm.  
Dome port inner radius 7cm thickness 1 cm

Corner blur due to field curvature

### Cylindrical port



**Cylinder  
(EP off-axis  
forward)**



Camera-to-object distance 1.3m. Cylinder inner radius 5 cm, thickness 1 cm. EP off the cylinder axis with EP about 2 cm from the inner surface

Corner blur from field curvature and astigmatism. Chromatic aberrations visible

Figure 4. Different simulated setups for assessing the image quality with flat, dome and cylindrical ports. The figure reports technical information on the setup and entrance pupil (EP) position.

### **3.1. Choice of Blender as Simulation Platform**

Blender was selected as the development environment due to several technical advantages:

- Free and open-source architecture,
- Cross-platform compatibility (Linux, macOS, Windows),
- OpenGL-based graphical interface,
- Extensive Python API enabling full software control,
- Large and active global community support.

Blender's Cycles rendering engine provides physically based rendering (PBR) capabilities essential for underwater simulation, including:

- Ray-traced refraction.
- Volumetric absorption and scattering.
- Subsurface scattering.
- Multiple camera models (rectilinear, fisheye).
- Depth of field.
- Motion blur.
- Flexible lighting configurations.

These features allow realistic modelling of light transport in participating media and complex optical systems.

### **3.2. Customization and Workflow Simplification**

Although Blender offers extensive functionality, its complexity may present challenges for non-expert users. POSER addresses this limitation by:

- Implementing custom menu interfaces to centralize relevant parameters.
- Encapsulating complex configurations into simplified user controls.
- Leveraging Python scripting for rapid reconfiguration of scenes.
- Enabling export and replication of experimental setups.

This design ensures reproducibility and facilitates sharing of fully parameterized simulation environments. Complex experimental models—comprising numerous interdependent variables—can therefore be easily distributed, reviewed, and reproduced by external users.

Figure 5 shows the Blender GUI from an example scene (underwater imaging for dome ports) with a customized graphical interface that includes programmed buttons

and informative panes with the relevant parameters and settings, otherwise scattered across Blender interface. The practitioners can easily understand the optical performances depending on dome size, sensor size, lens, aperture, focus distance.

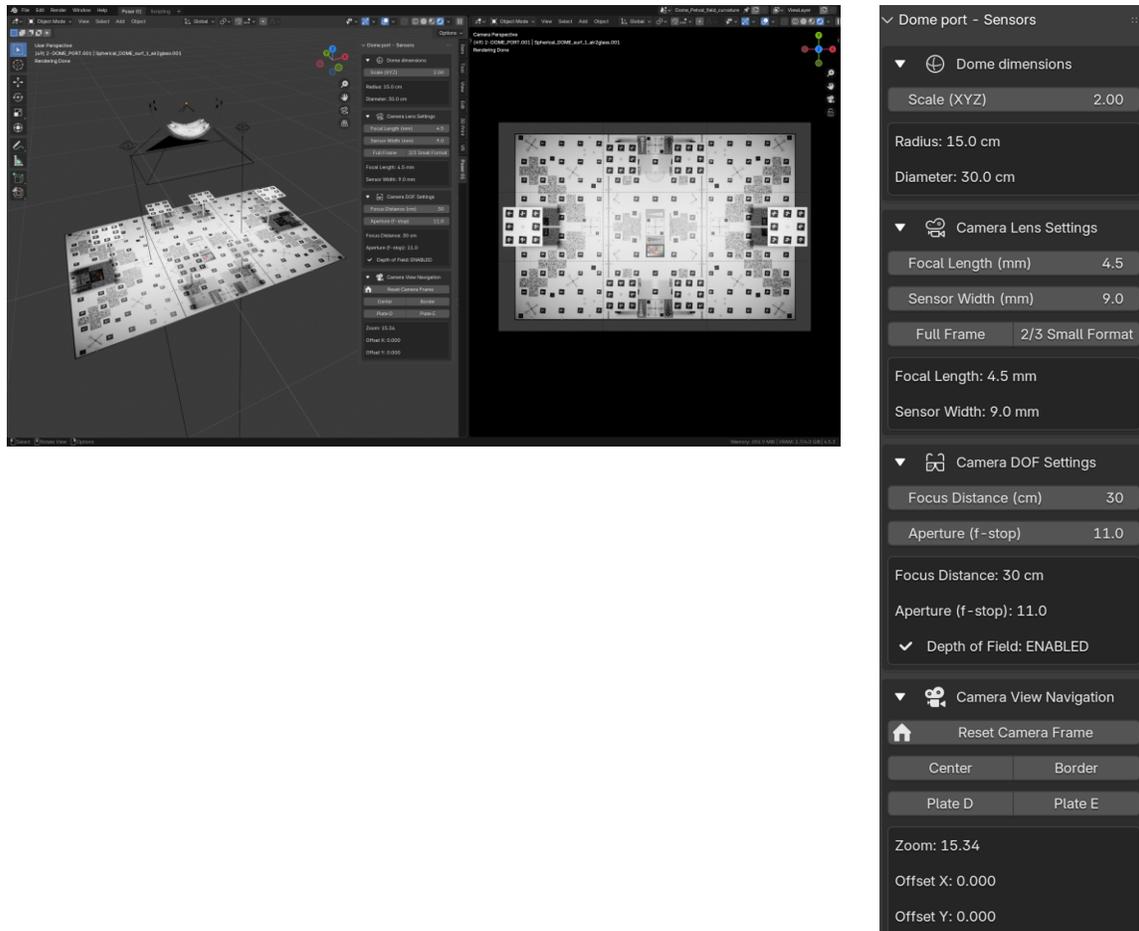


Figure 5. Example of a customized POSER GUI in Blender programmed through the Python API, enabling complex scene configuration through a reduced and simplified number of buttons and controls.

### 3.3. Virtual Reality Integration

POSER integrates Blender's VR capabilities through the VR Scene Inspection add-on, enabling immersive interaction with simulated underwater environments. Optionally, STEAM VR and OVR Toolkit enable desktop integration within the virtual scene for GUI interaction.

The use of VR supports:

- First-person survey visualization.
- Enhanced spatial perception of camera networks.
- Interactive inspection of acquisition geometry.

- Immersive teaching sessions.

Multiple pre-designed scenarios are incorporated to address application domains such as marine ecology, underwater archaeology, and subsea industrial metrology. The integration of VR/AR technologies enables both classroom-based and remote learning experiences, expanding accessibility and engagement.

Moreover, VR-based simulation allows safe and controlled replication of challenging environmental conditions, offering a practical training alternative when field access is limited. The growing availability and affordability of VR/AR/MR devices further support this educational approach, fostering knowledge transfer and collaboration across diverse professional and academic communities involved in underwater documentation and conservation.



Figure 6. An example of POSER VR capabilities using a Meta Quest 3 headset as hardware and Blender with STEAM VR and OVR Toolkit for the VR software implementation.

## 4. Modelling the Optical Physics of the Underwater Environment

### 4.1. Refraction

Refraction at water–air–glass interfaces is one of the main challenges distinguishing underwater photogrammetry from terrestrial or aerial applications. These effects influence image geometry and, consequently, the accuracy of 3D reconstructions. Additional optical phenomena, such as scattering, backscatter, wavelength-dependent light absorption, and light caustics (especially in shallow water), also play a critical role in image quality and must be considered during survey planning.

POSER builds on the developments presented by Nakath et al. (2022), where ray tracing in Blender’s Cycles engine was validated against physical experiments using both laboratory tanks and their digital twins. In POSER:

- Flat ports are modeled using planar mesh surfaces with glass shaders. If port thickness is neglected, the index of refraction (IOR) is set to the ratio between air and water (1/1.33). When thickness is considered, two surfaces are defined: air–glass (IOR 1/1.52 for BK-7 glass) and glass–water (IOR 1.52/1.33).
- Dome ports use single or double concentric spherical surfaces.
- Cylindrical ports, common in small micro-ROVs (e.g., Deep Trekker), are also included as a planned extension.

Different port shapes not only alter projection geometry but also affect focus and introduce optical aberrations, including field curvature and astigmatism (Menna et al., 2016, 2017). POSER allows simulation of these aberrations and supports single, stereo, and multi-camera configurations with multiple lens models (rectilinear, fisheye).

To approximate chromatic effects, which Blender does not natively model, images are rendered separately for the R, G, and B channels using wavelength-specific IORs, then combined into a final RGB image. This approach was tested with a full-frame 18 mm lens on flat, dome, and cylindrical ports in a controlled test field (Menna et al., 2017).

Water caustics, caused by sunlight refracting at wavy water surfaces or reflective submerged structures, and sometimes by artificial lights in semi-submerged environments (Nocerino et al., 2019), are simulated in POSER using Blender’s physical-based ocean modifier combined with random Voronoi textures (Figure 7). This produces temporally varying light patterns on the objects of interest, closely reproducing the visual and photometric challenges encountered in real underwater surveys.



Figure 7. Simulation of images taken over a shallow underwater archeological site consisting of Roman columns generated observing the sea bottom through water as if the image was acquired by an UAV. The image displays typical distortions and water caustics caused by waves.

## 4.2. Water Turbidity and Its Influence on Image Contrast

In terrestrial or aerial photogrammetry, the medium between camera and subject (air) is often negligible. In underwater photogrammetry, however, light absorption and scattering have a significant impact on image contrast, reducing both spatial resolution and measurement accuracy (Codevilla et al., 2015; Garcia and Gracias, 2011).

Selective, distance-dependent color absorption introduces characteristic color casts, typically ranging from blue in tropical waters to green in lakes (Jaffe, 1990). These effects reduce the clarity of features, alter apparent colors, and can limit the effectiveness of automatic feature detection in SfM pipelines.

POSER models these phenomena using Blender's volumetric rendering, allowing users to include:

- Light scattering and backscatter,
- Distance-dependent absorption,
- Water-selective color attenuation.

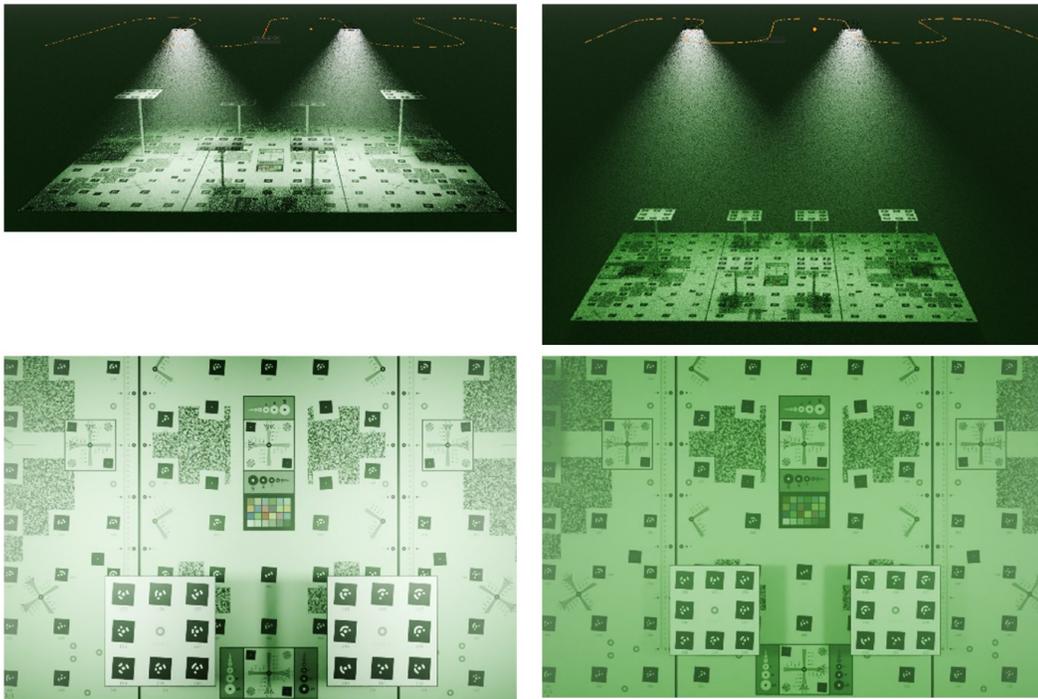


Figure 8. Test-object illuminated by two LED lights at about 30 cm from the camera in a scene simulating turbid green lake water. Two setups with the same ground sample distance are compared: a wide-angle lens at close distance (left column) and a longer focal length requiring the camera to be further away (right column). The increased water volume along the longer optical path results in stronger scattering, reduced contrast, and more pronounced wavelength-dependent color shifts, demonstrating the practical impact of turbidity on image quality and survey planning.

## **5. Multiple Pre-Designed Scenarios from Marine Ecology to Archaeology and Subsea Metrology**

POSER offers a collection of pre-designed simulation scenarios tailored to diverse underwater photogrammetry applications, supporting educational and research needs across multiple domains. These scenarios are crafted to replicate realistic conditions encountered in fields such as:

- **Marine Ecology:** Simulations include coral reef environments and benthic habitats, allowing users to explore challenges like complex geometries, varying light conditions, and biological complexity.
- **Underwater Archaeology:** Scenarios recreate submerged cultural heritage sites, shipwrecks, and artifacts, focusing on detailed 3D reconstruction of intricate structures with attention to scale, occlusions, and sediment effects.
- **Subsea Industrial Metrology:** The platform models inspection tasks common in offshore infrastructure, pipelines, and underwater machinery, emphasizing high-precision measurements under limited visibility and constrained access.

Each scenario integrates physical and optical parameters specific to its context, including water turbidity, lighting setups, camera configurations, and environmental geometry. This modular design enables users to select, modify, and extend scenarios to fit particular educational objectives or experimental goals.

## **6. POSER GitHub repository**

The open-source POSER GitHub repository (<https://github.com/GEOSS-UNISS/POSER/wiki/Key-Features>) documents the scenarios described in the previous section with detailed descriptions, parameter settings and example datasets. It supports community-driven development, encouraging contributions that expand scenario variety, realism, and functionality.

The repository provides:

- Installation instructions
- Key feature documentation
- Example scenes
- Tutorial modules
- Developer guidelines

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Examples	Add files via upload	2 years ago
Scripts/Metashape	Add files via upload	2 years ago
Wiki/Images	Add files via upload	2 years ago
LICENSE	Update LICENSE	2 years ago
README.md	Update README.md	7 months ago

**README** GPL-3.0 license

# POSER

an oPen sOurce Simulation platform for tEaching and tRaining underwater photogrammetry



POSER is an open-source platform designed to teach and train the fundamentals of underwater photogrammetry. It is funded by the ISPRS Educational and Capacity Building Initiatives and developed using Blender. The platform provides a scientifically sound and user-friendly environment for learning and experimentation, targeting students and researchers in marine archaeology, ecology, and subsea metrology.

## Learning by Doing with POSER

**About**  
 an oPen sOurce Simulation platform for tEaching and tRaining underwater photogrammetry  
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 GPL-3.0 license  
 Activity  
 2 stars  
 1 watching  
 0 forks  
 Report repository

**Releases**  
 No releases published

**Packages**  
 No packages published

**Languages**  
 Python 100.0%

Figure 9. Poser GitHub repository

## 6.1. Example Scenes

The Example folder in the POSER repository contains different example scenarios ranging from underwater imaging basics to camera calibration and SCUBA safety. An example of scenario for marine ecology studies is shown in Figure 10.

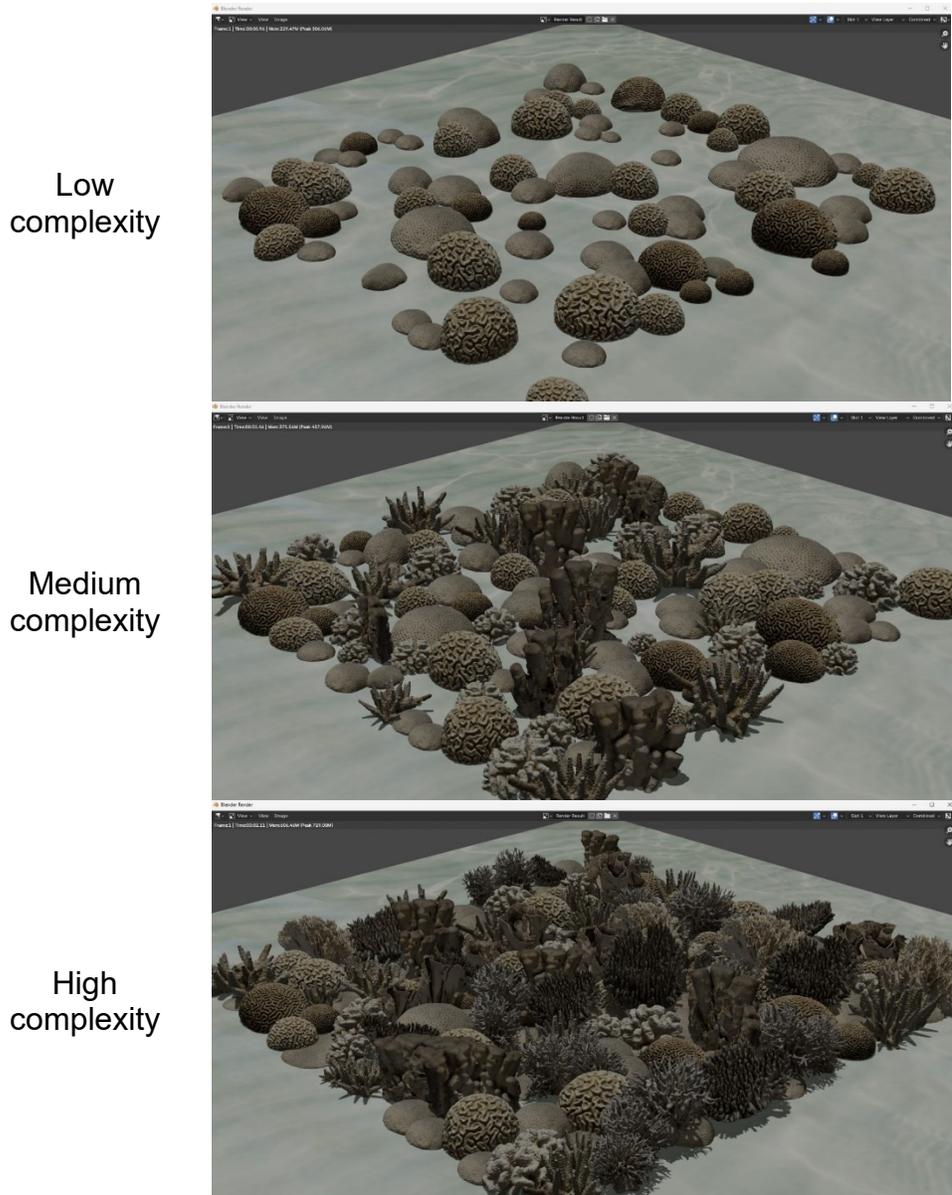


Figure 10. Coral reef scene with growing levels of 3D structural complexity.

In this example, the practitioner can practice designing the camera network geometry, tailoring it to accommodate varying levels of morphological complexity in the coral reef. The rendered images from the three different scenes are then processed with a SfM-MVS approach and compared to the available ground truth models.

Another practical example, shown in Figure 11, helps users plan safe underwater photogrammetry missions by combining dive physics, gas constraints, and survey paths, allowing both safety training, operational planning, and help reducing the actual underwater risk. The example considers the survey of a  $55 \times 7 \text{ m}^2$  coral reef in Moorea with underwater photogrammetry by a SCUBA diver. POSER simulates diver safety considerations for underwater photogrammetry by modeling pressure, gas consumption, and dive profiles.

#### Decompression Limits (NDL):

- Underwater pressure causes inert gases in body tissues to dissolve proportionally to depth.
- Divers must stay within the non-decompression limit (NDL) for safe ascent.
- Example: At 40 m depth, only ~10 min is safe without decompression stops; at 15 m, ~90 min is safe.

#### Air Supply Constraints:

- Standard air consumption (SAC) affects dive duration.
- Example: At 40 m, a diver can stay ~15 min; at 15 m, ~45 min, with standard tank capacity.

#### Simulation and Export:

- POSER allows exporting simulated dive profiles for planned photogrammetry paths using Python API.
- Profiles can be imported into Subsurface dive log software for detailed safety analysis.

#### Practical Example:

- A  $55 \times 7 \text{ m}^2$  reef survey in Moorea, with 20 parallel strips (~1,100 m total path) at 15 m depth, swimming at 0.2 m/s.
- Simulated dive duration: ~104 min, exceeding standard tank limits.
- Analysis in Subsurface shows decompression obligations and recommends using a larger tank setup (double 12 L tanks with SAC 15 L/min) for a single dive.

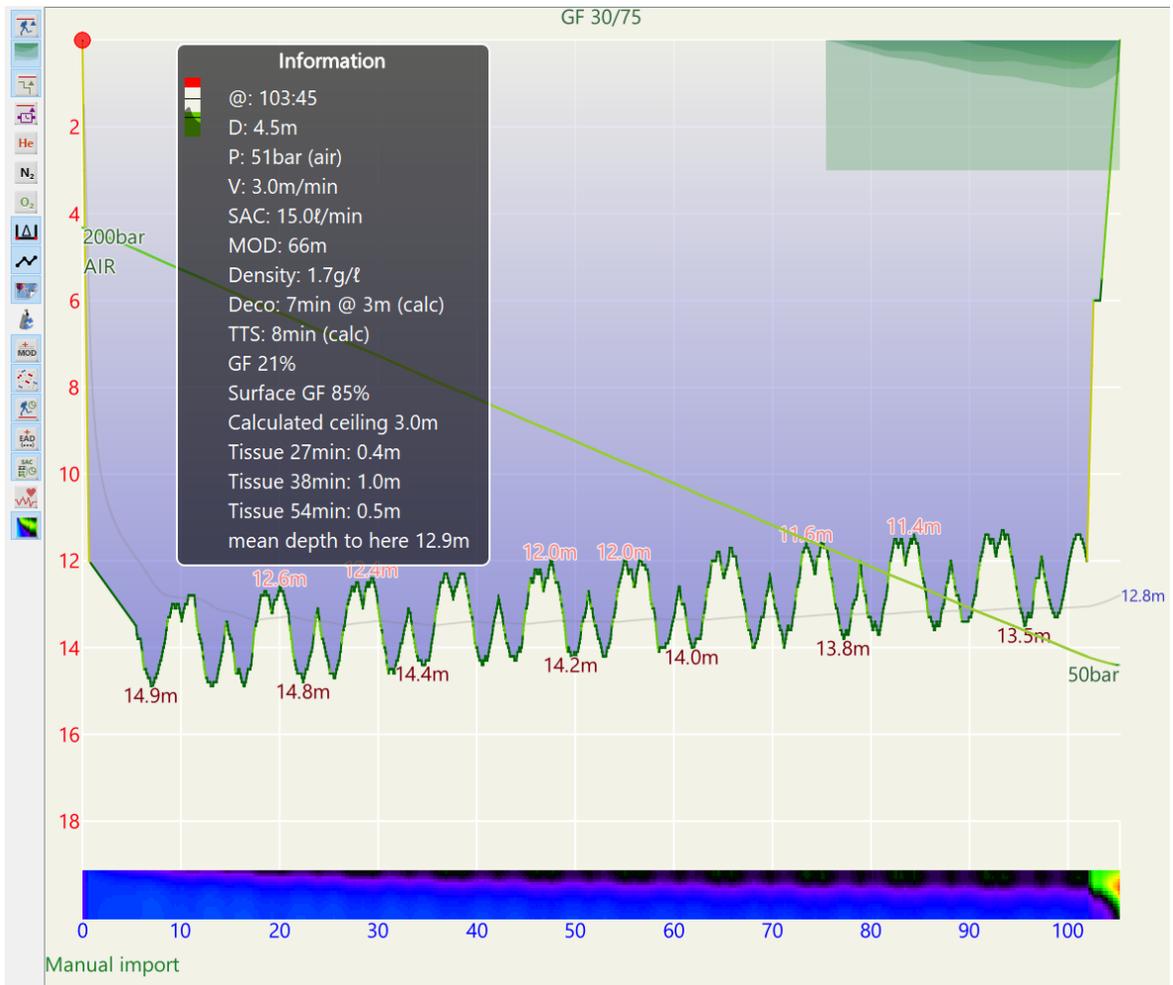
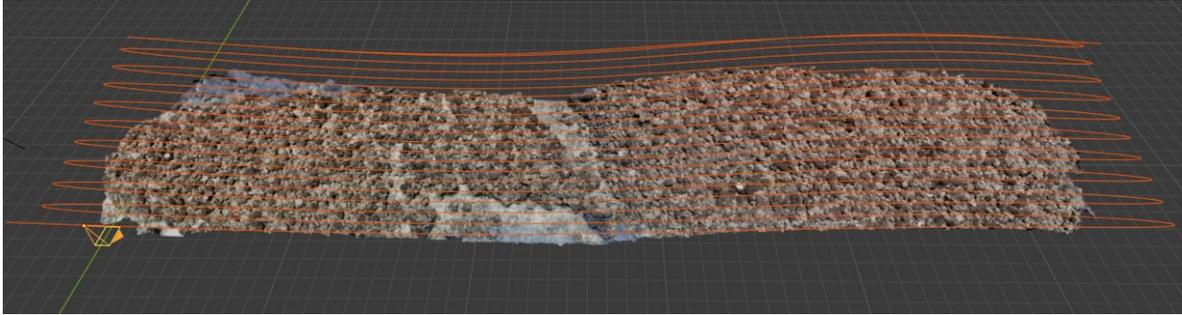


Figure 11. Example of dive profile related to a SCUBA dive operated photogrammetric survey exported from POSER simulator and imported in the opens source software Subsurface dive log.

## 7. Project dissemination International Deployment and Validation

POSER's preliminary results were presented at the TCII Photogrammetry ISPRS Midterm Symposia in Las Vegas (Menna et al., 2024). POSER learning material was extensively

used in different scientific tutorials and workshops, testing and validating its cross-disciplinary usability as well as applicability to research-oriented audiences:

- ISPRS Technical Commission II Symposium 2024 – Las Vegas.
- European Coral Reef Symposium 2024 – Naples.
- SUNRISE Summer School 2024 (Balletti et al., 2023, Teppati Losè et al., 2025).
- Breaking the Surface 2024.
- ISPRS TCII/7 Workshop 3D Underwater Mapping from Above and Below.
- Digital Heritage Forum in Abu Dhabi (2025).

Furthermore, POSER learning material is planned to be used for the tutorials planned to the following events:

- ISPRS 2026 Congress in Toronto
- SUNRISE Summer School 2026 in Italy



Figure 12. Underwater photogrammetry workshop with POSER learning material at the 2024 ECRS symposium in Naples, Italy.

## 8. Acknowledgments

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