Marine particles investigation by underwater digital holography

Victor V. Dyomin* [a], Igor G. Polovtsev [a], Alexandra Y. Davydova[a]
[a]National Research Tomsk State University, 36 Lenin Ave., Tomsk, 634050, Russian Federation

ABSTRACT

A hardware-software complex for non-contact investigation of marine particles is presented. The complex is based on digital holography principles and can be immersed in water, for example, to study plankton in a habitat. Special features of a submersible holocamera (or DHC sensor) are considered. Results of approbation of the complex during the Mission in the Kara Sea are presented. A new DHC sensor design is discussed.

Keywords: digital holography, plankton investigation, the Kara Sea, submersible holocamera

1. INTRODUCTION

Plankton research is an urgent problem of hydrobiology, ecology, fishery, etc. Holographic methods allow registration of large volume of the medium with particles and simultaneously provide acceptable resolution. At the same time, investigated particles are located in their natural habitat and are minimally disturbed. For the field study of plankton, submersible holographic cameras are used [1–11]. The holographic data obtained by such cameras contain information on the size, shape, and location of each particle in the volume under investigation, which allows one to estimate the concentration of particles, the particle size distribution, and their dynamic changes [1–15].

The hardware-software complex (the DHC sensor) presented in this article provides recording of digital holograms of plankton and reconstruction of images of plankton species in real time. The complex consists of a digital holographic camera, an electronics system for signal conversion, a system for linking with computer placed on board a ship, a battery, and a communication channel. The complex additionally includes a microwave sensor for measuring conductivity and depth and temperature sensors. The holocamera is based on in-line scheme [3, 13, 16] considered in Section 2.

2. PRINCIPLES OF HOLOGRAM REGISTRATION AND IMAGE RECONSTRUCTION

Modern technologies make it possible to use a CCD (or CMOS) camera in holography as a tool for recording interference patterns of the reference and object waves. Figure 1 shows the in-line scheme for recording the digital Gabor or in-line holograms [3, 13, 16]. A laser beam passes through a collimator forming the beam with the required cross section and then passes through the volume with investigated particles. As a result, the interference pattern of the reference wave (light passed round the particles) and the objective wave (light scattered by the particles) is formed. The camera registers this interference pattern and transmits it to the computer memory. Mathematical processing with special computational algorithms allows reconstruction of the spatial distribution of particles in the investigated volume (including three-dimensional coordinates of each particle), determination of the size, shape, velocity, and direction of movement of each particle [3, 14, 15], and their subsequent recognition [17].

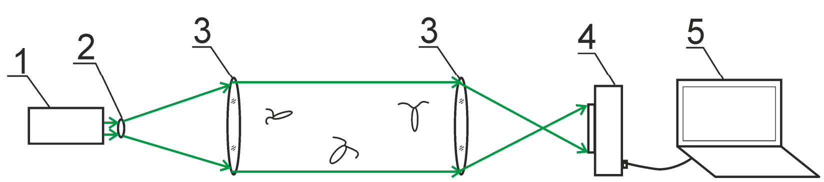

Figure 1. In-line scheme for recording digital holograms comprising laser 1, lenses 2 and 3, CCD/CMOS camera 4, and computer 5.

*dyomin@mail.tsu.ru; phone +3822529601; fax +3822529585

One of the popular applications of digital holographic methods is the research of marine particles, in particular, plankton in its habitat [1–11]. The main advantages of digital holography methods providing good perspectives for their application are:

- detailed investigation of each particle, sufficient for its identification, in the volume of the medium large compared to the particle size [17],

- obtaining information on the spatial position, orientation, and shape of each particle in real time [3, 14, 15],

- construction of 3D trajectory of motion of each particle [3, 14, 15].

3. PROBLEM FORMULATION

Traditionally, registration and analysis of qualitative and quantitative composition of marine particles is provided by collection of a plankton sample by a net from the required horizons and its routine manual laboratory processing. However, such a sampling technology, accepted in modern hydrobiology, cannot provide the data flow required for modern technologies of environmental monitoring [18]. In this aspect, the most important problem is maximum automation of registration and processing of information characterizing plankton in sea water. In principle, the appearance of such commercial technical solution allows such topical practical problems to be formulated that can be solved only in the monitoring mode:

1. Sub-satellite calibration of the spatiotemporal plankton distribution to assess the food base.

2. Assessment of the development dynamics of water areas by monitoring of plankton species diversity at stationary stations.

3. Monitoring of ecological situation at the stationary stations to prevent environmental disasters.

The combination of holography as a technique for two-dimensional recording of 3D particle ensembles and technique of video image recording resulted in the creation of digital holographic cameras that are best suited for solving of the above-formulated problem [1–11].

For technical implementation of the digital holographic camera intended for solving problems of environmental plankton monitoring, the following principles were formulated:

1. Replicability and commercial nature of the development.

2. Network principle of sensor organization in the information and measuring system, i.e., each sensor is communicated with each other sensor, and they all are communicated with the central processor which has a gateway to global information networking (principle of marine sensorics or the Internet of marine things).

3. Holographic data processing system is built in the camera, i.e. the central processor of the information-measuring system receives digital information that characterizes plankton from one side or another in full compliance with standards accepted in marine sensorics (aggregation into the existing marine data collection systems [19]) rather than holograms or plankton images.

4. Different problems are solved by one universal design; problems being solved can be changed by replacing the software that takes into account the peculiarities of data interpretation process (the principle of universality of the technical solution).

4. DESCRIPTION OF THE HARDWARE

The laser system (the illuminating module) and the CMOS camera (the receiving module) are placed in sealed enclosures rigidly fixed with respect to each other to form an investigated volume. The investigated volume is 500 mm long and 42 mm in diameter. The receiving and illuminating holocamera modules are shown in Fig. 2.

a b

Figure 2. Receiving (a) and illuminating (b) DHC modules.

The receiving and the illuminating modules are placed into a frame to form the volume under investigation illustrated in Fig. 1. The marine environment is very unfavorable for holographic equipment from the viewpoint of operating conditions. Therefore, in the designs of the submersible holographic chamber, sealed enclosures, sealed detachable electrical connections, and built-in power supply unit occupy a lot of space; organization of computational process and communication requires additional space; the resulting device is shown in Fig. 3

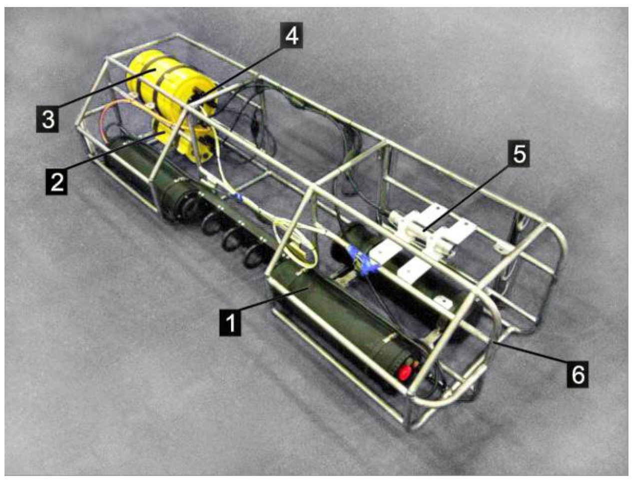

Figure 3. Measuring complex with DHC camera comprising DHC camera 1, hydrophysical module 2, information block 3, cable gland 4, microwave conductivity sensor 5, and frame 6.

Mathematical processing with specially developed computational algorithms makes it possible to implement the DHC technology of measuring marine particles that provides reconstruction of the map of spatial particle distribution in the volume under study and determination of three-dimensional coordinates, size, shape, velocity, and direction of motion of each particle for their subsequent recognition. For this purpose, the DHC submersible camera is supplemented with the information block providing:

- Organization of the computational process in the submersible device,
- Interaction of the DHC camera with sensors of hydrophysical parameters: microwave conductivity, pressure, and temperature,
- Communication with the central computer placed on board of a ship,
- Built-in power supply unit.

In this combination, the submersible measuring complex that implements the DHC technology of measuring marine particles has been realized. Communication with the ship computer on a research vessel is provided by a 10 core cable or a fiber-optic communication line (FOCL).

The device described in this paper has the following capabilities:

- 0.69 liter (length of 500 mm and diameter of 42 mm) volume investigated in one exposure,
- measurement of characteristics of particles moving with velocities up to 1 m/s,
- range of measurable conductivities of the medium 10–1500 μSm/m,
- speed of frame archiving no less than 5 fps,
- speed of real-time frame processing of 1 fps,
- depth profiling of plankton concentration, biomass, and average particle size,
- *in situ* classification of plankton by main taxonomic features,
- 1 Gb Ethernet FOCL with module placed on board of a ship,
- measurement of hydrophysical parameters at the observation point,
- diving depth up to 500 m.

5. MISSION TO THE KARA SEA

The capabilities of the DHC camera were tested in the Kara Sea during summer Marine Arctic Mission of the Institute of Oceanology of the Russian Academy of Sciences (IO RAS) on the research vessel Academician Mstislav Keldysh [3]. The submersible complex was dived to a predetermined depth, and during its ascent, a video sequence of holograms was recorded and hydrophysical water parameters were measured. Data were transferred to the ship computer for the subsequent processing of holographic images and reconstruction of plankton particles. The maximum immersion depth was 250 m. The paper presents the results obtained for several ship parking. The map with the depicted working areas is shown in Figure 4 (a). Figure 4 (b) shows the photograph of the complex before diving into the Kara Sea.

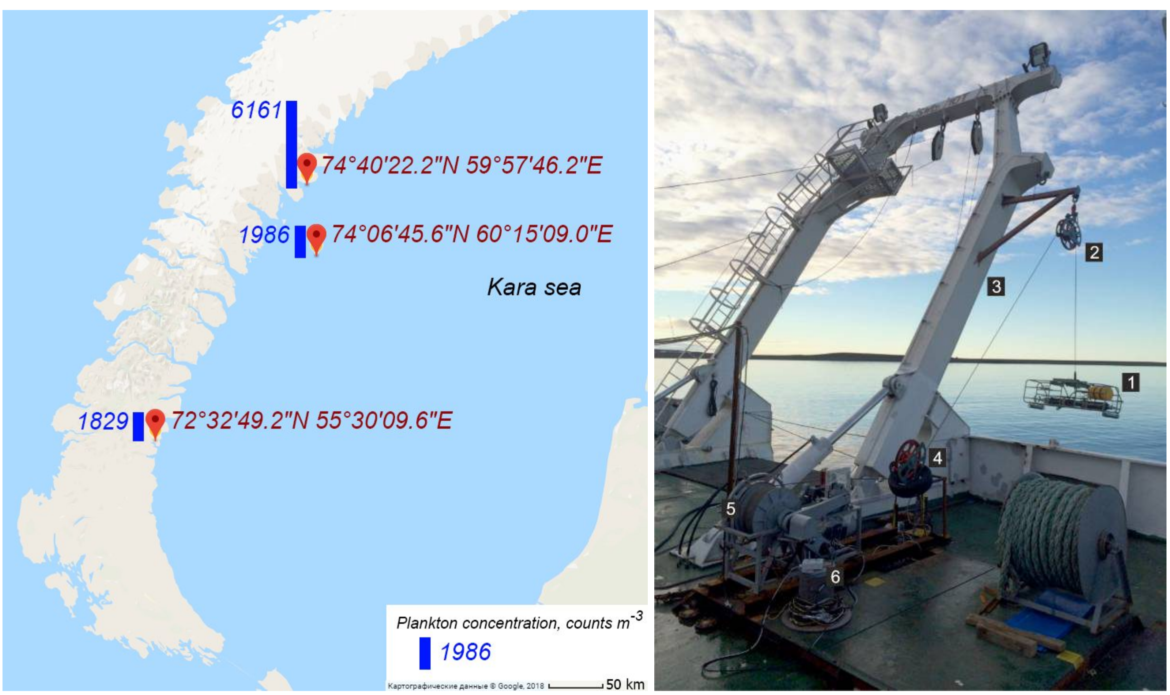

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Figure 4. (a) Map depicting working areas during 66 Arctic Mission of the IO RAS. Points of registration of holograms with the DHC camera are marked with orange labels. The coordinates of stationary locations are indicated by orange color, and the plankton concentration (including phyto- and zooplankton; in counts per cubic meter) are indicated by blue color. (b) DHC camera on the aft deck of the research vessel Academician Mstislav Keldysh. Here 1 indicates the submersible complex with the DHC camera, 2 indicates the FOCL electric winch, 3 indicates the P-frame forage, 4 and 5 indicate the cannonade blocks, and 6 indicates the winch control panel.

During immersion and uplifting of the DHC camera a video sequence of holograms was recorded, and water hydrophysical parameters – conductivity and temperature – were measured. The recorded digital holograms and the measured parameters were transferred to the computer placed on board the ship for subsequent processing and reconstruction of plankton particle holographic images. Figures 5 and 6 show the results of hologram processing that demonstrate the capabilities of solving practical problems associated with sub-satellite calibration of the spatiotemporal plankton distribution aimed at assessing the food base as well as determining the development dynamics of water areas by means of monitoring the plankton species diversity at the stationary stations. Figures 5 (a)–(c) show particle concentration, temperature, and microwave conductivity distributions with depth in the water area of the Kara Sea near Novaya Zemlya for 3 stationary stations (coordinates of ship stationary location were (a) 74°40'22.2"N, 59°57'46.2"E; (b) 74°06'45.6"N, 60°15'09.0"E; and (c) 72°32'49.2"N, 55°30'09.6"E). The reliability of the obtained data on particle concentrations is proved by a comparison with the data on the hydrophysical parameters (the correlation coefficient was 76–78%). Figures 5 (d)–(f) show the two-dimensional displays of holographic images of the investigated volume with plankton particles at different depths of camera diving, and the corresponding histograms of particle size distributions are shown in Figures 5 (g)–(i).

The morphological parameter is used for automatic classification [17], and the marine particles with sizes more than 200 µm are subdivided into 5 taxonomic groups: Copepoda, Cladocera, Rotifera, phytoplankton and other (Figure 6(a)). The reliability of the data of the DHC-classification is proved by a comparison with the data on the accepted manual classification performed by the operator. The correctness of classification is about 73% [17]. Figure 6 (b) shows an example of the classification result on a 2-dimensional representation of the holographic image of the investigated volume. The rectangles circumscribed around particles determine the morphological parameters, and the length of the rectangles determines the particle size. The blue rectangle represents the result of automatic classification of the Copepoda, and the red rectangle is for phytoplankton. The concentrations of plankton, including phytoplankton and zooplankton, are indicated with blue on the map shown in Figure 4 (a) (this is the concentration of particles that was recognized by the software as plankton, in contrast to Figure 5, where the concentrations of all marine particles are shown). Figure 6 (c) contains a more detailed information on the concentration of plankton of different taxonomic groups, for example, the Copepoda concentration on August 13 was higher than on August 8 or 11. The order of the data obtained with the DHC camera is comparable to that obtained by the traditional method [20].

6. NEW CAMERA DESIGN

The results of our studies demonstrate the efficiency of application of holography in marine sensor systems that provide:

- The possibility of detecting zooplankton particles *in situ* with the help of the DHC camera with real-time assessment of their sizes, species, and concentrations at different horizons with frequency of no less than 1 fps.

- Arrays of digital holograms with reference to depth, temperature, and microwave conductivity have been obtained.

- The performance of the DHC camera has experimentally been confirmed at depths down to 200 m and greater.

At the same time, significant overall dimensions of the device greatly complicate its operation with this holographic camera under field conditions. Therefore, a new camera design with a folded working volume and a mirror-prism system was proposed. In this arrangement, the device is more compact (Figure 7), and the registered volume is 1 liter.

We are also considering the development of a miniDHC sensor (a DHC network option with a compact holographic block).

Thus, testing during the summer Marine Arctic Mission of the IO RAS has confirmed the correctness of the embedded technical solutions and has allowed us to formulate a list of measures to further improve the DHC camera and methods of its application for successful introduction of oceanological research into practice.

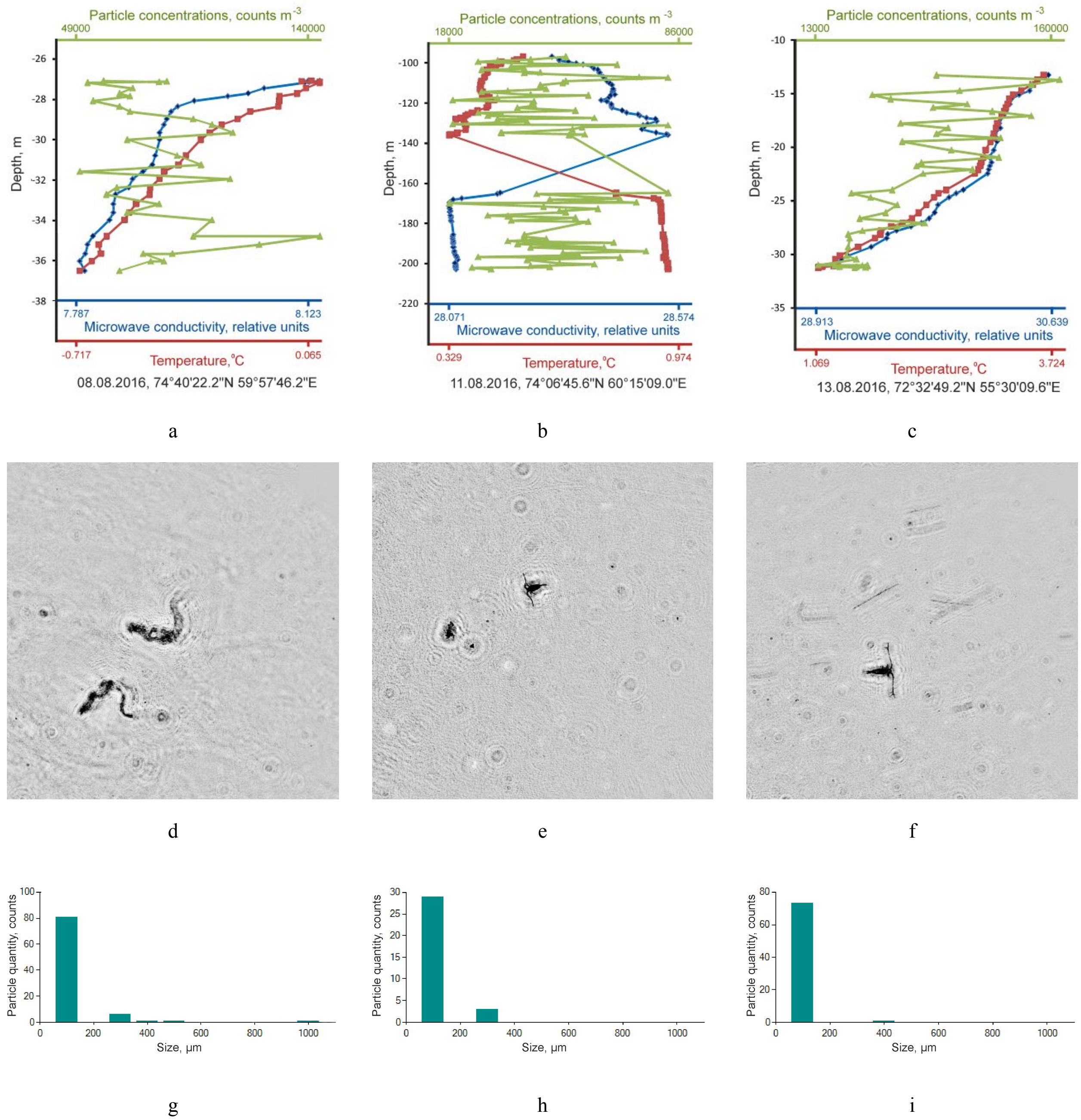
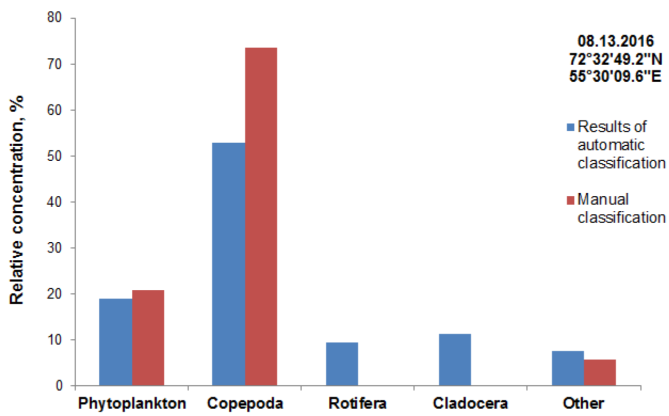


Figure 5. Distributions of plankton concentration (green curves), microwave conductivity (blue curves) and temperature (red curves) with depth registered on August 8, 2016 (a), August 11, 2016 (b), and August 13, 2016 (c) in the water area of the Kara Sea near Novaya Zemlya. The two-dimensional representation of the holographic image of the investigated volume with plankton particles and the corresponding histograms of their size distributions are shown at a depth of 34.8 m below sea level on August 8, 2016 (d) and (g); at a depth of 203.44 m below sea level on August 11, 2016 (e) and (h); and at a depth of 21.78 m below sea level on August 13, 2016 (f) and (i).



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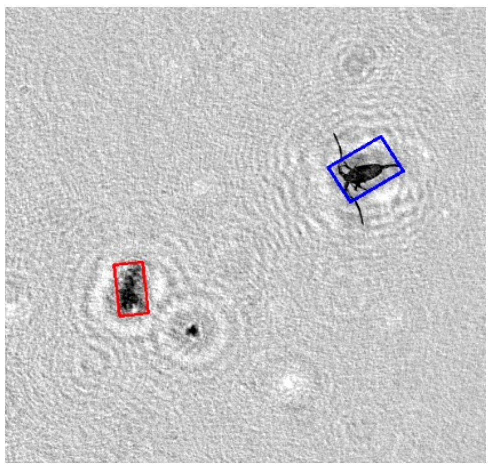

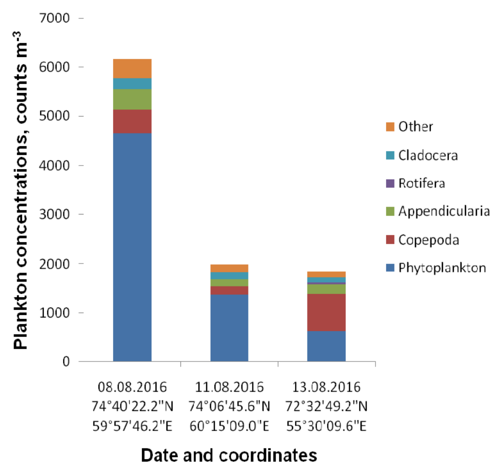

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Figure 6. (a) DHC plankton classification by the holograms registered in the water area of the Kara Sea near Novaya Zemlya compared with the data on the accepted manual classification with the operator. (b) Example of classification result on a 2-dimensional representation of holographic image of the investigated volume. The blue rectangle represents the result by the automatic classification for Copepoda, and the red rectangle is for phytoplankton. (c) Concentrations of plankton of different taxonomic groups for 3 stationary locations of the ship.

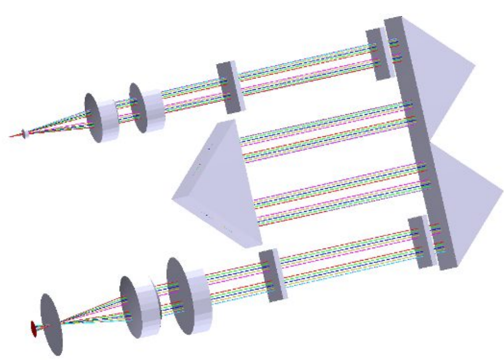

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Figure 7. In-line scheme with a folded working volume for digital hologram recording.

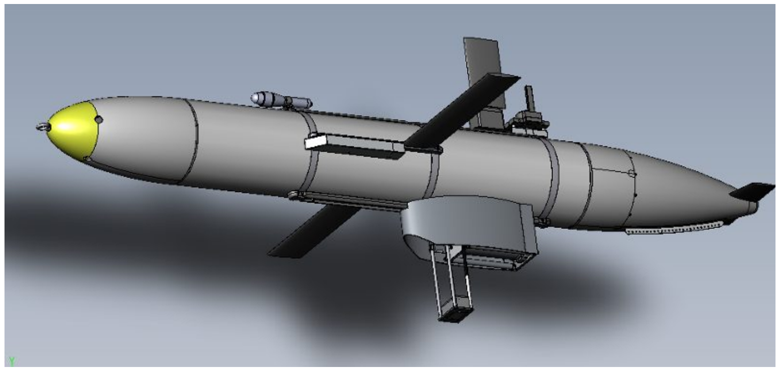

Figure 8. MiniDHC camera on a glider hanger (project).

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