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Video Article

Quantitatively Measuring *In situ* Flows using a Self-Contained Underwater Velocimetry Apparatus (SCUVA)

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Abstract

The ability to directly measure velocity fields in a fluid environment is necessary to provide empirical data for studies in fields as diverse as oceanography, ecology, biology, and fluid mechanics. Field measurements introduce practical challenges such as environmental conditions, animal availability, and the need for field-compatible measurement techniques. To avoid these challenges, scientists typically use controlled laboratory environments to study animal-fluid interactions. However, it is reasonable to question whether one can extrapolate natural behavior (i.e., that which occurs in the field) from laboratory measurements. Therefore, *in situ* quantitative flow measurements are needed to accurately describe animal swimming in their natural environment.

We designed a self-contained, portable device that operates independent of any connection to the surface, and can provide quantitative measurements of the flow field surrounding an animal. This apparatus, a self-contained underwater velocimetry apparatus (SCUVA), can be operated by a single scuba diver in depths up to 40 m. Due to the added complexity inherent of field conditions, additional considerations and preparation are required when compared to laboratory measurements. These considerations include, but are not limited to, operator motion, predicting position of swimming targets, available natural suspended particulate, and orientation of SCUVA relative to the flow of interest. The following protocol is intended to address these common field challenges and to maximize measurement success.

Video Link

The video component of this article can be found at http://www.jove.com/video/2615/

Protocol

1. To begin this procedure, we ensure that all SCUVA components have sufficient battery power, recording tape (for the high-definition or HD video camera), and function properly. Depending on the flows to be measured, select video camera resolution and frame rates that yield best results for digital particle image velocimetry (DPIV).[1,2]
2. Prepare the laser and camera housings for use by cleaning the o-ring grooves and o-rings with a clean towel or wipe. Spread manufacturer provided o-ring grease evenly on the o-rings and replace them in the housing grooves. In addition, clean the laser and camera housing apertures to prevent laser sheet deformation and marks on the camera housing lens.
3. Check the o-ring seals by placing both empty housings in a tub full of water. Weighted objects will need to be placed on top of the housings to submerge them since the housings float when empty. After 5 to 10 minutes, remove the housings from the tub and towel dry the outside. Check whether there is any moisture inside the housings. Also consider using disposable, paper moisture strips during the pressure test to indicate whether there is moisture in the housings after the test.
4. After the housings pass the pressure test, place SCUVA components inside the housings.
5. Attach high-intensity discharge (HID) light pods to the camera housing. Ensure that the lights are oriented in such a way that they illuminate the area directly ahead of the camera and operator, and do not interfere with maintaining grip on handles and operation of camera controls.
6. In a low light environment, ensure that the laser beam is properly aligned relative to the optical lens installed in the laser housing. When properly aligned, the laser/lens combination will create a vertical sheet of light that is oriented perpendicular to the camera housing. For safety, use a temperature-sensitive sheet of paper to determine laser sheet orientation.
7. Using SCUVA attachments and the rigid, extendable arm, connect the laser housing and the camera housing to each other. Ensure that the housings are firmly attached and that the housings cannot rotate with respect to each other. It is critical that the laser sheet remains oriented perpendicular to the camera's field of view throughout the measurement.
8. Due to the current capabilities of SCUVA, measurement dives can only be conducted in low-light locations or at nighttime to prevent natural light interference with the laser sheet. Therefore, we recommend waiting until dusk or later before entering the water.
9. Turn on the camera housing before entering the water. The camera housing has a built-in electronic moisture sensor that provides visual warnings (flashing LED lights) in case of moisture in the camera housing. The sensor only works when the camera housing is on.

10. Immerse SCUVA in water and attach the apparatus to yourself using a line. Once attached to the apparatus, release SCUVA to determine the buoyancy characteristics of the device. Depending on the buoyancy characteristics, attach buoyancy foam or lead weights to one or both housings to ensure neutral buoyancy and prevent rotation of the apparatus in water.
11. Next, switch on the laser and hold the apparatus stationary. Position the laser using the extendable arm sufficiently far from the diver to minimize measurement of diver-induced flows. Any measurements of diver-induced flows near the target introduce error and are not used for subsequent analysis. Adjust the camera zoom until the field of view frames the target and surrounding fluid.
12. While keeping the apparatus stationary, focus the video camera on the laser sheet until particles appear sharp and in focus. Once the laser sheet plane is in focus, switch the camera to the manual focus mode. This will prevent the camera from refocusing on any objects that appear in the field of view during measurement,resulting in blurred particles in the laser sheet.
13. To calibrate SCUVA, place an object with known dimensions in the laser sheet within the video camera's field of view. Record for several seconds. After the dive, an image will be extracted from this video sequence to determine a calibration constant that converts the field of view size from units of pixels to cm. If at any time the operator adjusts the field of view size be re-position the extendable arm or changing the camera zoom during the dive, steps 12 and 13 will need to be repeated.
14. Begin the dive by descending to the working depth. Upon finding a target, the environmental bulk flow properties need to be determined. If present, the current direction will dictate apparatus and diver positioning relative to the target during measurements. The direction of bulk flow surrounding the target can be inferred by observing bubbles exhaled from the diver and noting their lateral motion. In addition to bubbles, a small quantity of fluorescent dye (i.e., fluorescein) can be released to determine the current direction. Since diver-generated flow can be a source of DPIV measurement error, the diver should not be located upstream of the target. In addition, the laser sheet should be positioned parallel to the direction of current so as to maximize particle residence time within the laser sheet, thereby minimizing DPIV errors. However, if no current or bulk flow is present, diver and SCUVA positioning relative to the target are unrestricted.
15. Position SCUVA to illuminate and record the fluid motion surrounding a target. If attempting to record the flow surrounding a moving target first predict the location of the target, and then position SCUVA to the predicted location while remaining motionless. As the target moves through the camera's field of view, begin recording. If the target is motionless, frame the target and surrounding fluid in the video camera's field of view and begin recording while remaining motionless. The operator should refrain from rotational and out-of-plane motions during video recording since these motions result in erroneous DPIV results. Therefore, measurements collected during rotational and out-of-plane diver motions will not be used for further data analysis.
16. Once video collection is complete, turn off all components of SCUVA and restore the laser arm to its retracted position. Remove SCUVA from the water and detach the camera and laser housings from the arm. Rinse or soak the apparatus in fresh water before drying to prevent rusting of the apparatus. Once the housings are dried, remove components from the housings, and recharge and replace batteries if needed for another dive.
17. Connect the video camera to a computer and extract video from the HD tape by using a HD video software package (i.e., Adobe Premiere Pro or iMovie). After the video is extracted, determine the range of video to be converted into a series of images for DPIV analysis. Ensure that the pixel aspect ratios and extracted image sizes match the HD video settings.
18. These images are imported to a DPIV processing program (i.e., DaVis or MatPIV). After proper selection of calibration constant and image capture parameters, which are prompted from the DPIV software package, velocity fields can be generated from consecutive particle images. Additional post-processing steps, depending on the quality and types of measurements, can also be applied.[3]

Representative Results:

When the protocol is done correctly, the particle images surrounding the target will be sharp and easy to distinguish. Using the particle fields captured *in situ* by SCUVA's video camera (Figure 1A) and a DPIV processing software package, velocity fields of flow surrounding the target (Figure 1B) will be revealed. Vectors in the velocity field indicate magnitude and direction of the local flow velocity. If sufficient video is collected to provide a time series of images, a time series of velocity fields can also be determined.

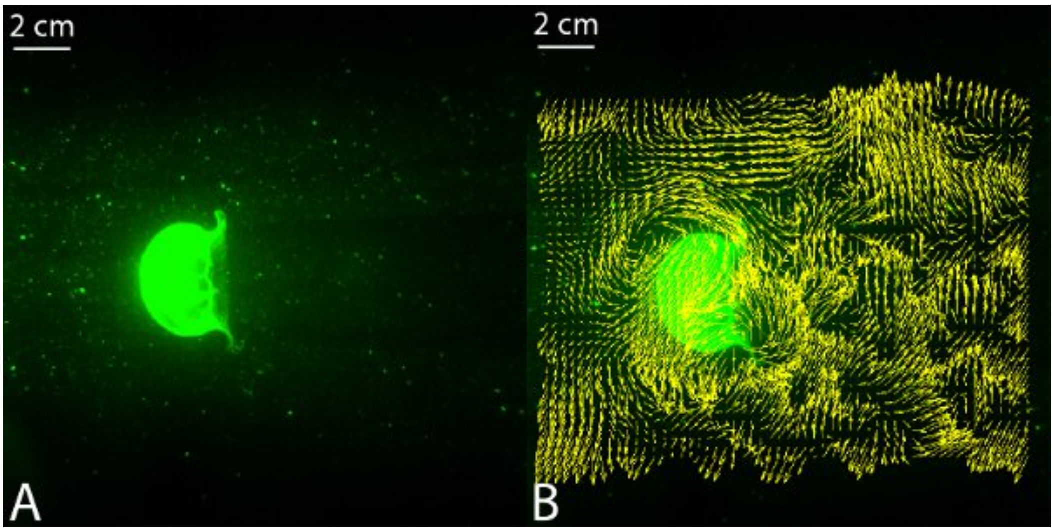

Figure 1 Measured *in situ* particle fields (A) surrounding *Aurelia labiata*. Corresponding velocity field (B) with yellow vectors indicating flow direction and magnitude.

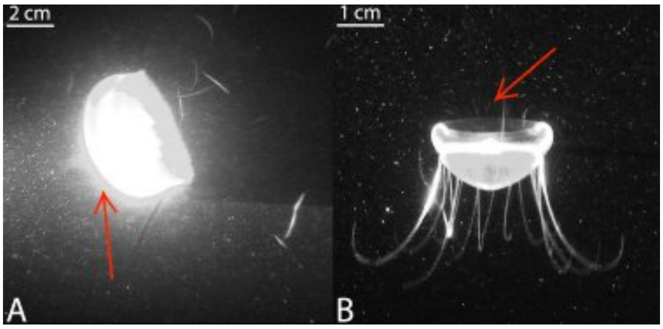

Figure 2 *In situ* particle fields surrounding *Mastigias sp.* and *Solmissus sp.* (A and B, respectively). Red arrow in A indicates a region of high reflectivity, which results in saturation of the image, making it difficult to distinguish between particles and the target. Red arrow in B indicates a region of streaking that results when the flow rate is not sampled at a high enough frequency.

Discussion

A potential constraint in the field is the need for particles in the flow, which are necessary to implement digital particle image velocimetry (DPIV). In coastal water, suspended particulate matter exhibits sizes on the order of 10 μm in diameter and concentrations between 0.002 and 10 per mm ^{3}.[4] Additional studies using a submersible holocamera for particle detection confirm sufficient presence of seeding particles to perform DPIV in ocean water.[5] During open sea and coastal ocean diving, we have found that particle densities and sizes are not a constraint for conducting *in situ* DPIV.

Aside from particle densities and sizes, another concern relevant to DPIV measurements is the homogeneity of particle concentrations.

Qualitatively, if a region within an interrogation window has greater particle concentrations than another, the velocity magnitude generated by the DPIV analysis will be biased towards the region with higher particle concentrations. Therefore, SCUVA measurements must be conducted where particle concentration variability is minimized. We found thatcle concentrations are relatively constant during particle concentrations are relatively constant during dives where the diver is suspended in the middle of the water column. However, particle fields in benthic environments have the potential for inhomogeneity due to resuspension of particles by environmental or diver-induced flows near the sea floor. Care must be taken to minimize disruption of particles during measurements in benthic environments. To the authors' knowledge, a formal analysis of errors generated by inhomogeneous particle concentration fields has not been conducted in either laboratory or field conditions, and should be a subject for further consideration in a separate publication.

Several different issues should be considered when preparing and conducting *in situ* experiments using the protocol. While recording, the operator is instructed to remain stationary and refrain from all out-of-plane and rotational motion. This request is simple in theory but difficult in practice, and these measurements require advanced diving skill to be completed successfully. Out-of plane and rotational motions of the operator result in erroneous DPIV data. However, in-plane motions can be corrected by using in-house software.[6] It is recommended to the operator to practice buoyancy control for several dives before using SCUVA to maximize measurement efficiency.

Besides buoyancy considerations, the operator should be aware of the target flow direction. Flows that travel out-of-plane relative to the laser sheet will not yield reliable DPIV results, and the operator should orient SCUVA to capture these flows most effectively. In addition, the position of the diver relative to the target must be selected so as to minimize diver-induced flow in the measurements. Diver-induced flow introduces error to the target flow, and measurements that include diver effects should not be used for further analysis.

In the event that the target has a highly reflective surface, the fluid region surrounding the target will be strongly illuminated, making it difficult to distinguish nearby individual particles from surrounding fluid (region indicated by red arrow, Figure 2A). Filters or polarizers can be added to the laser or camera housings to reduce the intensity of the laser light captured by the video camera sensor. If this is not possible due to logistical constraints and limited access to equipment, post-processing of images using in-house software can provide sufficient correction by subtracting from the images the elevated pixel intensities near the target. Another consideration that affects the quality of DPIV data is whether particle streaks are present. If particle fields have regions of streaking (indicated by red arrow, Figure 2B), the video camera is recording at a frame rate too low to resolve these high velocities. By increasing the frame rate, particle streaking can be reduced. However, this results in a reduction of light reaching the video camera sensor and makes the particle field look dimmer. If the video camera has the ability to manually set aperture settings, increase the aperture setting to prevent dimming of the particle field. Determining the optimal device settings may require multiple dives with SCUVA before successful data collection.

Disclosures

No conflicts of interest declared.

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