An Optical Imaging System for Capturing Images in Low-Light Aquatic Habitats Using Only Ambient Light

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S1. DEPLOYMENT AND UNDERWATER OPERATION

The optical imaging system (OIS) was deployed in the kelp forests on the northern edge of the South La Jolla State Marine Reserve (SMR; 32.8263°N, 117.2901°W) in approximately 14 m water depth from July 10 to 23, 2018 (Figure S1a). It captured 24 images every 12 minutes between 05:00 and 21:00 (i.e., at least one hour before sunrise and after sunset) to ensure that no potentially usable light conditions were missed for image acquisition. Images were captured under aperture priority mode (aperture: *f*2.8) as uncompressed, raw image files with a 16:9 aspect ratio. The focusing distance of the lens was set at 0.3 m in air so that a fish one meter away from the camera in water would be in focus. This was determined using equations in Jenkins and White (2001) to compute the focusing distance for thick lenses, and we have included a MATLAB R2016b (MathWorks, Natick, MA) script to calculate this in the GitHub repository (https://github.com/cpagniel/FishOASIS/blob/master/hardware/FishOASIS_lens_focusing_dist_code.m). The ISO (International Standards Organization) sensitivity of each image was automatically set by the camera between 50 and 409,600. The white balance was also automatically set by the camera.

The OIS was mounted by divers to an L-bracket (for landscape images) on a 1 m tall u-post set in a 50 × 50 × 10 cm concrete block (Figure S1b). It could also be mounted directly to the stand for portrait images. The battery pack was placed on the concrete block and cable-tied to two eyebolts set in the concrete block. A HOBO Pendant temperature/light 8K data logger (Onset Computer Corporation, Bourne, MA) was attached to the camera housing to measure seawater temperature (in °C) and ambient light (in lux). To correct for the ambient light spectra, a DGK Color Tools WDKK Waterproof Color Chart was deployed in the field of view of the camera at a distance of 2 m. To approximate the distance of fishes from the camera, distances to various stationary objects always visible in the images (e.g., rocks, kelp holdfasts, cinderblocks) from the camera were measured using a transect tape.

To demonstrate the OIS's ability to synchronize its clock with that of a passive acoustic recorder, the OIS was deployed alongside a SoundTrap ST4300 (Ocean Instruments, Auckland, NZ) four-channel acoustic recorder equipped

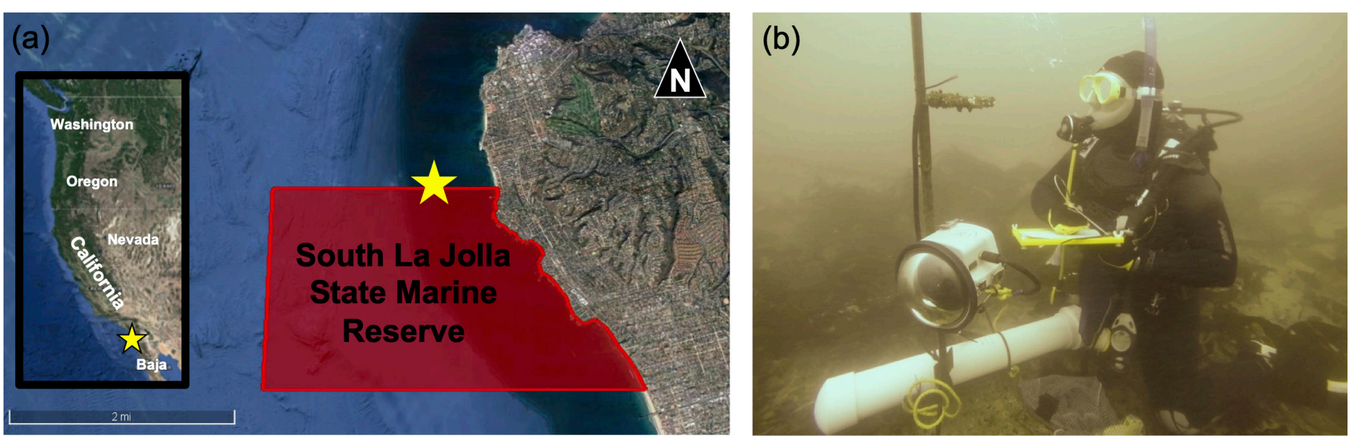

FIGURE S1. (a) Location of deployment of optical imaging system off the coast of La Jolla, California, on the northern edge of the South La Jolla SMR (yellow pentagram). In the inset, the location of the larger map is shown as a yellow star off the coast of southern California. (b) Optical imaging system deployed by a diver. *Image credit: A. Cusick* with four HTI-96-MIN hydrophones (High Tech Inc., Long Beach, MS), whose sensitivity was –201 dB V/µPa with 36 dB pre-amplifier gain. The acoustic recorder sampled continuously at 48 kHz.

S2. DATA ANALYSIS

All of the data analysis described below was performed offline (i.e., after the data had been downloaded from the OIS).

S2.1 Image Analysis

All raw images were color-corrected using a modified version of the Sea-thru method (Akkaynak and Treibitz, 2019). This method requires a range map of the scene from raw images and uses an updated underwater image formation model (Akkaynak and Treibitz, 2018) to estimate distinct backscatter and attenuation coefficients for all colors. For our images, we were only able to obtain range maps for pixels very close to the camera. Because our goal was to improve visibility (and not to obtain accurate color reconstruction), we extrapolated range information for the rest of the scene.

Fishes in these images were manually identified to the species level (when possible) by an analyst using a custom-built MATLAB R2016b graphical user interface. The analyst used contextual information such as the fish's shape and position in the water column as well as preceding and succeeding images and a list of expected species in the deployment location to identify each fish. Images of individual fish were extracted from the raw images so that another analyst could review the initial species identification. When the analyst was unsure of the fish species, a professional fish taxonomist from the Scripps Institution of Oceanography Marine Vertebrate Collection was consulted. Image quality was classified based on the ability of the trained analyst, not the professional fish taxonomist, to identify a fish to the species level. If the species of the majority of the fish in an image could easily be identified, the image was considered of high quality. All post-processing tools are available online from https://github.com/cpagniel/FishOASIS/.

S2.2 Acoustic Analysis

Because the frequency of fish sounds previously recorded in this area generally does not exceed 2 kHz (Pagniello et al., 2019), acoustic data were decimated from 48 kHz to 4 kHz by first lowpass filtering the data with a Chebyshev Type I infinite impulse response filter (8^{th} order, normalized cutoff frequency of 0.8/12, passband ripple of 0.05 dB) and subsequently down-sampling the filtered data. Spectrograms of the acoustic data were generated by dividing the time series into equal-length segments of 512 samples having 90% overlap, applying a Kaiser-Bessel window of $\alpha = 2.5$ to each segment, taking the fast Fourier transform (FFT) of each segment, and averaging the squared magnitude of the FFT of overlapped, windowed segments. The overall sensitivity (–78 dB re 1 µPa/counts) of the PAS was applied to the spectrograms to yield calibrated values of spectral density (dB re 1 $\mu Pa^2/Hz$). Spectrograms of all the acoustic data between 05:00 and 21:00 were manually reviewed for the 610 Hz and 690 Hz synchronization tones played by the miniature speaker as well as the sound produced by the actuation of the camera shutter. The start time, duration, and frequency bandwidth of these sounds were logged using the logger feature of the MATLAB R2013b program Triton (Wiggins, 2003).

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TABLE S1. Approximate recording duration (days) for different data storage capacities and sampling rate combinations estimated from power consumption of 720 Wh battery pack and image size

	1 img/12 min	12 img/12 min	24 img/12 min
256 GB	32.3[a]	9.4[b]	4.7[b]
512 GB	32.3[a]	18.9[b]	9.4[b]
768 GB	32.3[a]	22.3[a]	14.1[b]

[a] indicates the optical system would be battery limited
[b] indicates storage limited.

TABLE S2. Fish species photographed during a 14-day camera deployment in the South La Jolla State Marine Reserve kelp forest from July 10 to July 23, 2018. Taxa are listed in order of decreasing total counts.

Common and Scientific Name	Life Stage	Life Stage Counts	Total Counts
Señorita (*Oxyjulis californica)*	Adult	4,421	4,421
Blacksmith (*Chromis punctipinnis)*	Adult	18	2,739
	Juvenile	2,698	
	Unknown	23	
Unidentifiable Fishes		1,191	1,191
Rock Wrasse (*Notorynchus cepedianus)*	Adult	1,120	1,120
Kelp Bass (*Paralabrax clathratus)*	Adult	420	420
Opaleye (*Girella nigricans)*	Adult	295	295
California Sheephead (*Semicossyphus pulcher)*	Terminal	118	234
	Initial	114	
	Unknown	2	
Halfmoon (*Medialuna californiensis)*	Adult	78	78
Kelp Perch (*Brachyistius frenatus)*	Adult	74	74
Bait Ball (> 20 Fish) of Unidentifiable Fishes	Unknown	73	73
Kyphosidae	Unknown	71	71
Pacific Barracuda (*Sphyraena argentea)*	Adult	6	58
	Juvenile	52	
Pacific/California Jack Mackerel (*Trachurus symmetricus)*	Adult	24	57
	Unknown	33	
Sargo (*Anisotremus davidsonii)*	Adult	30	30
Garibaldi (*Hypsypops rubicundus)*	Adult	22	25
	Juvenile	3	
Broadnose Sevengill Shark (*Notorynchus cepedianus)*	Adult	24	24
Black Surfperch (*Embiotoca jacksoni)*	Adult	8	8
Yellowtail Amberjack (*Seriola dorsalis)*	Adult	5	6
	Juvenile	1	
Bat Ray (*Myliobatis californica)*	Adult	5	5
White Seabass (*Atractoscion nobilis*)	Juvenile	1	3
	Unknown	2	
Barred Sand Bass (*Paralabrax nebulifer)*	Adult	2	2
Sebastidae	Unknown	2	2
Painted Greenling (*Oxylebius pictus)*	Adult	1	1
Shovelnose Guitarfish (*Rhinobatos productus)*	Adult	1	1

Total Fishes:	**10,938**
Total Fishes Identified to Species Level:	9,601
Total Fishes Identified to Family Level:	73
Total Unidentifiable Fishes:	1,264
Total Adult Fishes:	6,786
Total Juvenile Fishes:	2,755
Total Unknown Life Stage Fishes:	60

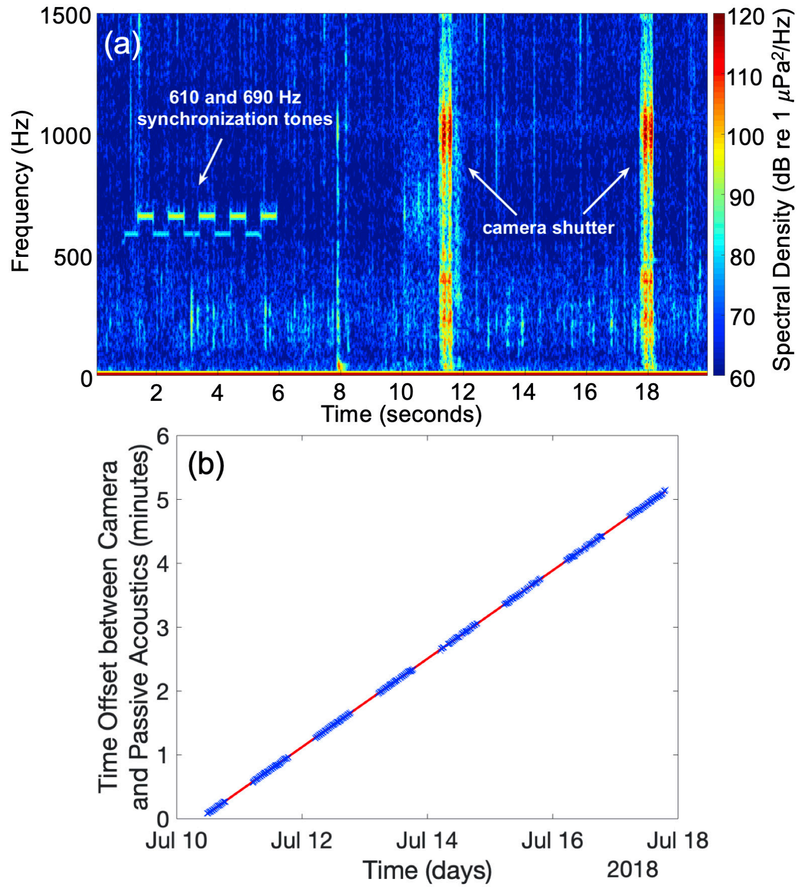

FIGURE S2. (a) Spectrogram showing 610 and 690 Hz tones used to synchronize optical imaging system and passive acoustic system clocks as well as sound produced when the camera shutter was actuated. (Spectrogram parameters: Kaiser-Bessel window with a = 2.5, sample rate = 4 kHz, 512-point fast Fourier transform with 90% overlap. Color represents spectral density (dB re 1 mPa^2/Hz).) (b) Clock drift of passive acoustic recorder relative to the clock time of the optical imaging system. Blue crosses indicate the times of the first 610 Hz inter-calibration tones of each sequence during which camera was operational. Demonstrating the linearity of the drift is the red least-squares fit line (y = 0.00048001x + 0.075834) in units of minutes since July 10, 2018, at 11:36:51 PST (i.e., the start of the deployment).

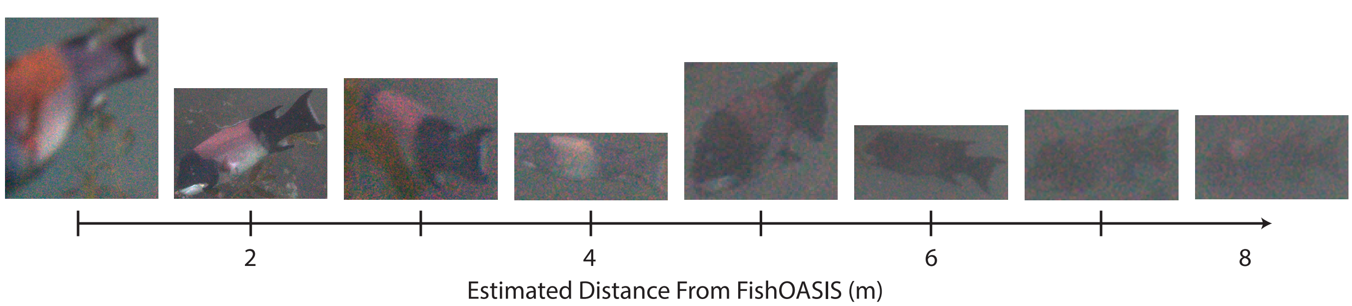

FIGURE S3. Image quality of terminal adult California sheephead at increasing distances from the optical imaging system. All images were captured between 10:30 and 11:15 local Pacific standard time. Fish were at about the same depth at all times.