Development of boat-based fluorescence imaging lidar for coral monitoring

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Abstract. A boat-based coral observation system has been developed using lidar (light detection and ranging) techniques for large area coral monitoring. Lidar is an optical remote-sensing technique using pulsed laser. In this study, a fluorescence imaging lidar system consisting of an ultraviolet (UV) pulsed laser with a wavelength of 355 nm and a gated ICCD camera has been designed and tested. Most reef-building corals have fluorescent proteins that emit blue-green fluorescence on UV excitation. On the other hand, dead coral skeletons, sand, rocks and algae show no blue-green fluorescence. The fluorescence lidar system harnesses this property. Seabed images are recorded by emitting UV pulsed laser and receiving fluorescence by the gated ICCD camera synchronized with the laser. Because the exposure time is very short, the sunlight background effect for the lidar image is suppressed, and this makes it possible to detect weak UV excited fluorescence even in the daytime. Live versus dead determination of corals from fluorescence images can be confirmed by verifying the coral image pattern and fluorescence intensity. The performance evaluation test of the system was conducted in a testing basin, and both the imaging and bathymetry performance for pseudo-coral targets were confirmed down to 30 m depth. Additionally, coral observations were conducted using a glass-bottom-boat at Taketomi Island, Okinawa, Japan. The information of live coral distribution along the boat track was obtained successfully over a 1.4 km transect, in depth from 2 to 15 m, and validated within 30 minutes of survey time.

Key words: Coral, Fluorescent protein, UV, Lidar, Monitoring.

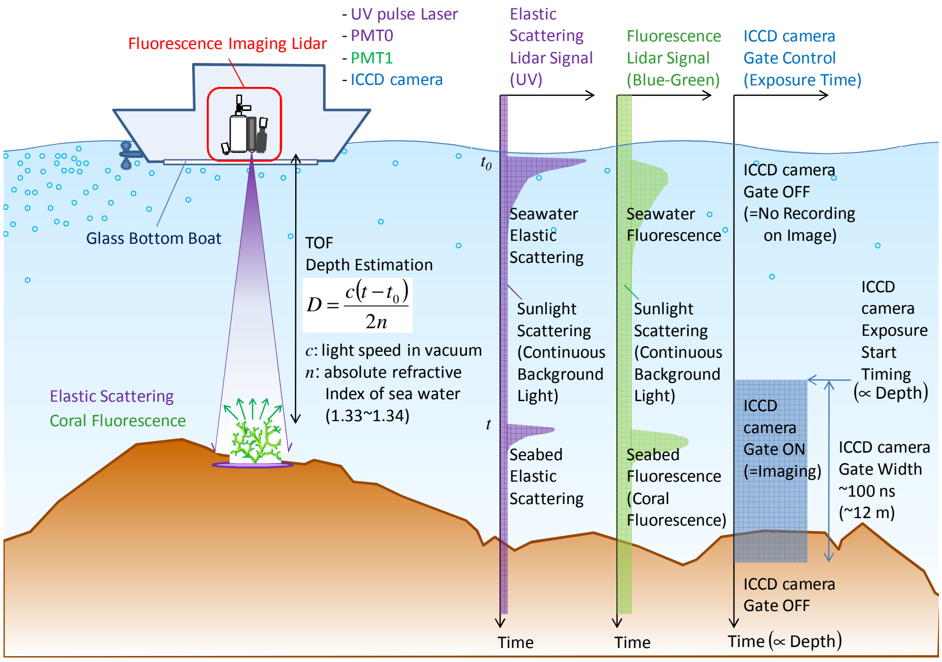

Figure 1: The conceptual overview of the boat-based fluorescence imaging lidar for coral monitoring.

Introduction

Coral reefs are fragile ecosystems affected by global warming and ocean acidification (Hoegh-Guldberg et al. 2007), and it is predicted that these changes of the ocean environments will continue (IPCC Report 2007). Therefore, monitoring of coral reefs over a large-area and long-term is particularly important in terms of the environmental impact assessment of global climate change.

The two typical methods currently used for annual coral monitoring over large coral reefs are snorkeling/diving investigations (Biodiversity Center of Japan 2009) and satellite remote sensing (Mumby et al. 2004). The former method can generate detailed information on corals, though the investigation area is small. Due to health and safety concerns for underwater operations in deeper areas, the monitoring points tend to set toward shallow reefs, though hermatypic corals are distributed down to around 30 m depth. The latter method can provide coral cover data over large areas, though the investigation results have uncertainties due to inadequate resolution of satellite imagery, sea surface effect and light absorption effect in seawater. Both methods have strict limitations for their observation conditions. Especially, snorkeling/diving investigations require calm sea conditions and the satellite remote sensing requires cloudless sky. A new observation method is required to generate abundant coral monitoring data in large coral reef areas.

Lidar (light detection and ranging) is an optically active remote sensing technique, and a potential tool for monitoring coral reefs as an airborne or a boat-based system (Hardy et al. 1992; Brock et al. 2006). In former study, lidar system is used for measurement of seabed shape with green laser in coral reef areas, especially for massive stony corals. The purpose of this study is to develop a new coral monitoring method with fluorescence imaging lidar with UV laser that can be used for large area monitoring from several meters to 30 m depth, and for a coral viability check (Fig. 1).

Coral monitoring using fluorescence properties

Many corals have innate fluorescent proteins near the surface of their tissues. Especially, most species of Acroporidae and Faviidae, which are typical hermatypic corals distributed from 0 to 30 m depth, have blue-green fluorescent proteins (Alieva et al. 2008). Fig. 2 shows the UV-excited emission spectrum of an Acroporidae colony near Taketomi Island, Okinawa, Japan. These data were taken at night by an underwater spectrometer with a near ultra-violet LED illumination with a peak wavelength of 365 nm. This spectrum shows strong green fluorescent protein (GFP)-like fluorescence peaks around 490 and 510 nm, and a weak chlorophyll-*a* peak around 680 nm. If corals are dead, fluorescent proteins will be denatured and will not work as biopigments. If algae or seaweeds are attached to a dead coral skeleton, they show only as red fluorescence of chlorophyll-*a* at a wavelength of around 680 nm. Therefore, UV induced fluorescence between 450 and 550 nm is considered a good indicator of the presence of live coral.

The images in Fig. 3 show a damaged colony near Taketomi Island at intervals of a few months. The upper three are daytime 0.5 m square quadrat photographs, and the lower three are nighttime UV-LED illuminated fluorescence quadrat photographs. From these photos it is easy to visually determine if the coral colony is dead or alive by the intensity of blue-green fluorescence.

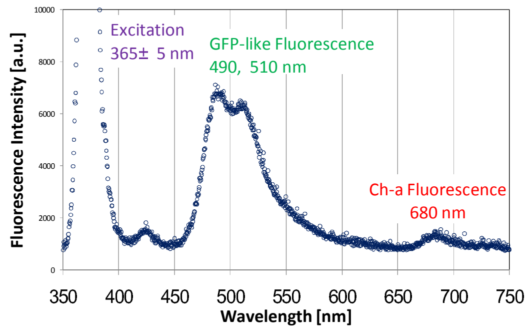

Figure 2: The emission spectrum from UV-excited coral.

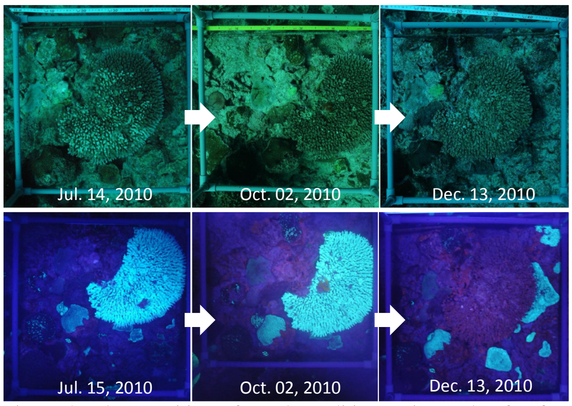

Figure 3: The transition of coral condition at intervals of a few months (top: daytime quadrat photos, bottom: nighttime UV-excited fluorescence quadrat photos).

Fluorescence imaging lidar system

Lidar technique can be applied for underwater environmental investigations. In this study, we use Nd:YAG (THG) pulsed laser at 355 nm wavelength for the transmitter, and a gated ICCD camera for the receiver. The UV pulsed laser illuminates the seabed beneath the boat for only around 7 ns, and the gated

ICCD camera is exposed for ~100 ns, which includes the coral fluorescence detection timing coincident with the pulsed laser (Fig. 1). Since the exposure time of the gated ICCD camera is very short, the lidar system is able to visualize the coral fluorescence image even in daytime without being disturbed by the sunlight. Additionally, because of the short exposure, lidar image blurring due to the boat's motion is negligible. The laser-induced fluorescence near the sea surface can be eliminated from a lidar image by adjusting the start time of the exposure dependent on the depth of the sea. Specifications of the lidar system are shown in Table 1 and the block diagram is shown in Fig. 4.

Lidar Performance Test

For evaluating the resolution of the system and target depth dependent coral visualization sensitivity, test observations were performed in a 35 m deep basin at the National Maritime Research Institute, Japan. The lidar system was installed on a mini boat with observation windows at the bottom. The control units of the lidar system were set on the testing stage and connected with sensor units on the mini boat by cables. Nine pseudo-corals made from plastic containing fluorescent agent were used as lidar detection targets of the size 0.9 x 0.9 m, and put on an underwater movable floor that can be adjusted between 5.5 and 34 m depth.

UV pulsed Laser (Quantel CFR400)	Type	Nd:YAG (THG)
	Wavelength	355 nm
	Energy	90 mJ / pulse
	Pulse Width	7 ns
	Repetition	10 Hz (max)
	Spread Angle	45 to 350 mrad
gated ICCD camera & collective lens (Hamamatsu Photonics C10054-22, Fujinon C22-17A-M41)	Type	Image Intensified CCD with Gate function (usual OFF)
	CCD pixel	768 * 494
	Diameter	70 mm
	Field of View	35 to 660 mrad
DGPS position & attitude measurement device (Septentrio PolaRx2e@)	Type	Single frequency DGPS 3 Antenna System
	Position Accuracy	1 m
	Attitude Accuracy	0.3 deg
Sonar depth sounder (Tamaya Technics TDM9000)	Frequency	200 kHz
	Spread Angle	200 mrad
	Range	1 to 100 m
	Depth Accuracy	0.02 m

Table 1: The specifications of the fluorescence imaging lidar system for coral monitoring.

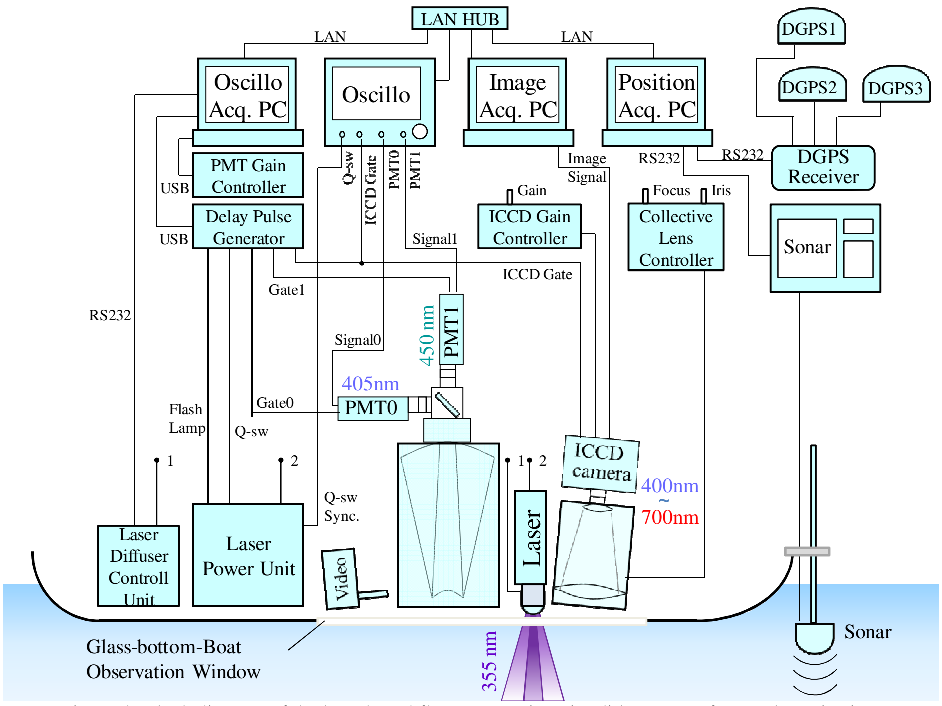

Figure 4: Block diagram of the boat-based fluorescence imaging lidar system for coral monitoring.

The testing basin was filled with clear freshwater during the testing of the fluorescence imaging lidar. The movable floor was set to the depths of 5.5, 10, 15, 20, 25 and 30 m. The gate timing and gain of the ICCD camera were optimized manually for each depth. The captured fluorescence lidar images are shown in Fig. 5. Clear fluorescent images were recorded down to 30 m depth (the maximum testing depth).

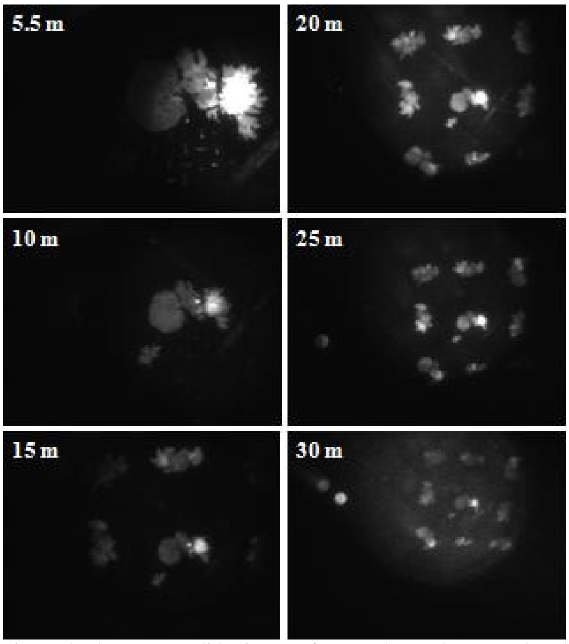

Figure 5: Fluorescence lidar images for pseudo coral targets placed at the depths of 5.5, 10, 15, 20, 25 and 30 m in a freshwater testing basin of 35 m deep.

Additionally, as a second test, real coral observations were performed during Jan. 18-20, 2011, with the fluorescence imaging lidar system mounted on a glass-bottom-boat at Taketomi Island, Okinawa, Japan. The sensor part of the lidar system was installed just above the bottom window of the boat. The boat position was recorded by DGPS system with about 1 m accuracy (Fig. 6).

Fig. 7 shows three images of the same coral colonies taken by different observation methods: the usual daytime underwater photograph with a 0.5 m square quadrat, the nighttime underwater UV-LED illuminated fluorescence photograph with a 0.5 m square quadrat, and the daytime boat-based fluorescence lidar image.

The patterns in the fluorescence image observed by the boat-based fluorescence imaging lidar system were confirmed to be consistent with the UV fluorescence quadrat photograph taken by diver.

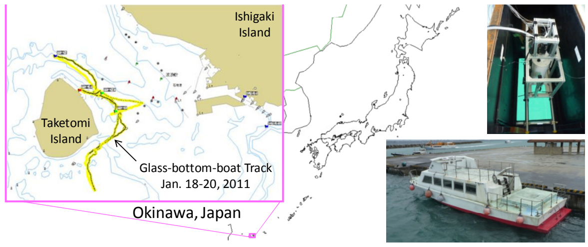

Figure 6: Tracks of the glass-bottom-boat based fluorescence image lidar observations around Taketomi Island, Okinawa, Japan.

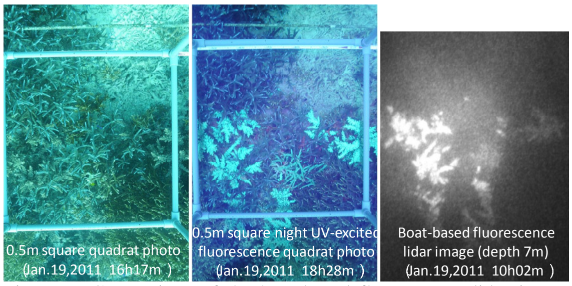

Figure 7: Comparison of the boat-based fluorescence lidar image (right) with daytime underwater quadrat photo (left) and nighttime underwater UV-excited fluorescence quadrat photo (center).

Observations and Results

More than 70,000 lidar images were recorded along the track of the glass-bottom-boat near Taketomi Island coral reef area during the testing period noted above. Data recording repetition was 4 Hz in most cases and the laser spread angle was 45 mrad in all cases. Four seabed fluorescence images are shown in Fig. 8 as examples. The substratum can be confirmed by the difference in fluorescence contrasts and image patterns, which can be used to assess the presence of live coral.

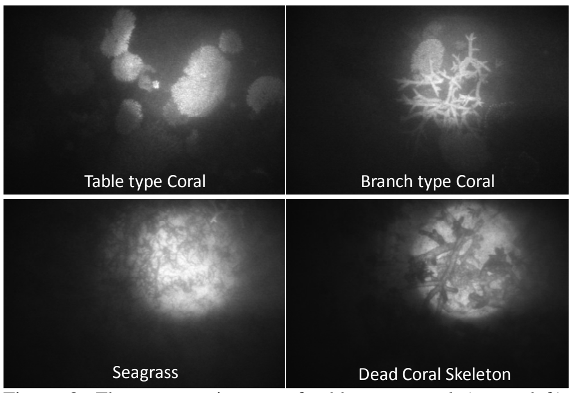

Figure 8: Fluorescence images of table type coral (upper left), branch type coral (upper right), seagrass (lower left) and dead coral skeleton (lower right).

The coral distribution data can be produced from the substratum visual assessment of fluorescence images registered with the DGPS position, based on the spatial pattern of fluorescence. The coral distribution data are shown in Fig. 9, which is a part of the whole observed dataset, and forms a simple observation line from shallow water of about 2 m depth to a deeper area of about 15 m depth with around 3.0 km/h speed covering around 1.4 km in distance.

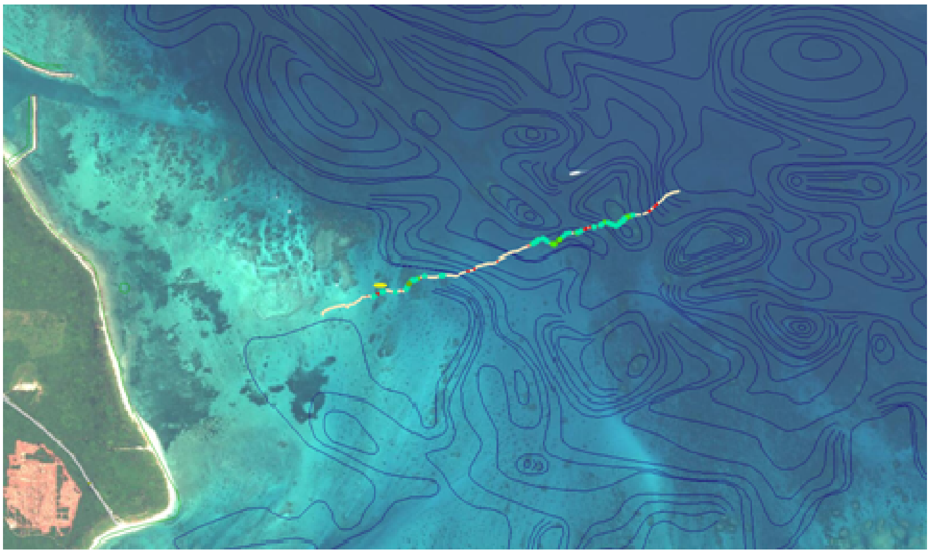

Figure 9: Coral distribution observed by the boat-based fluorescence imaging lidar in the eastern area of Taketomi Island, Okinawa, Japan (green points: table type coral, blue points: branch type coral, white points: sand, red points: dead coral skeleton) overlapped with WorldView-2 satellite image and bathymetry data. The yellow point shows SCUBA diving investigation area with a 20 m x 1 m belt-transect and the coral cover was around 43 %.

Discussion

We developed a boat-based fluorescence imaging lidar system for coral monitoring. This system achieves an intermediate resolution and intermediate coverage area for coral monitoring between diving investigations and satellite remote-sensing. It is expected to be a part of cooperative coral monitoring technology. Additionally, this system can cover deeper areas than satellite remote-sensing for coral viability check. Such monitoring data are considered to be important for the environmental impact assessments of global climate change.

Acknowledgement

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