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Spectral Discrimination of Live and Bleached Corals: A Case Study on *Turbinaria peltata* (Esper, 1794) Using Field Spectroscopy

Nandini Ray Chaudhury, Ashwin Gujrati, T.V.R. Murthy
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Abstract

Scleractinian corals represent the foundation species of reef ecosystems. Bleaching is a physiological, cellular response to environmental stresses wherein marine invertebrates including corals expel their endosymbiont, unicellular microalgae or zooxanthellae from their host tissues. Field spectroscopy helps to characterize the health of corals in terms of reflectance spectra or spectral signatures, i.e. reflected light as a function of wavelength. This chapter reports a case study on spectral discrimination of in situ hyperspectral signatures of live, apparently healthy and bleached corals collected from a single colony of *Turbinaria peltata* (Esper, 1794) sampled from Laku Point reef in Gujarat coast of India. Derivative analyses on the in situ reflectance data identify five narrow windows in the visible light region (green and red light regions) to spectrally discriminate live and bleached coral polyps of the *T. peltata* species. This study highlights the potential of field spectroscopy in characterizing coral health in situ through non-invasive sampling.

Keywords: coral, coral bleaching, *Turbinaria peltata*, spectral signature, derivative analysis

1. Introduction

Corals are foundation species of coral reef ecosystems. Hermatypic or reef-building corals are exclusively polypoid, marine organisms which belong to the taxonomic order: Scleractinia of Class Anthozoa and Phylum Cnidaria. Scleractinian corals are different from other Anthozoans like soft corals and sea anemones thanks to their continuous hard calcium carbonate crystal exoskeleton. Accordingly, corals can be ecologically divided, but cannot be systematically classified, into reef-building (hermatypic) and non-reef-building (ahermatypic) corals [1]. Hermatypic corals commonly contain millions of endosymbiotic, unicellular, dinoflagellate algae or zooxanthellae. Hence, they are also known as zooxanthellate corals. On the other hand, ahermatypic corals mostly lack zooxanthellae [1].

There is a mutualistic symbiosis between the host coral polyps and the endosymbiont, unicellular, microalgae named zooxanthellae. Zooxanthellae owe their common name due to their yellow-brown colour and belong to the genus *Symbiodinium* sp. to eight lineages (clades A–H) based on phylogenetic classification [2]. Zooxanthellae photosynthesize and help host corals to meet their energy requirements from photosynthetic products, while the host provides them intracellular space and essential nutrients like nitrogen, inorganic carbon. The photosynthetic pigments within zooxanthellae along with the host tissue and calcium carbonate exoskeleton pigments give corals their essential colours. Bleaching is one of the common expressions of physiological response to environmental stresses wherein corals or any other zooxanthellate marine invertebrate organisms expel the zooxanthellae from their host tissues. The expulsion of zooxanthellae and the resultant reduction of zooxanthellae pigment concentration per host cell lead to visible paling/fading or whitening of the host organism. This process is known as bleaching. Bleaching results in varying levels of mortality of the host organism depending on the severity of stress. Thermal stress is considered as the principal cause for coral and other zooxanthellate invertebrate bleaching, while other environmental factors can also cause bleaching either independently or synergistically with thermal stress [3]. These abiotic factors include exposure to supra-optimal irradiances of visible radiation, exposure to ultraviolet (UV) radiation, low-temperature thermal stress, salinity changes, sedimentation and desiccation due to low-tidal exposure [3, 4]. Thermal stress alone or in combination with exposure to high irradiances of both visible and UV radiation leads to photoinhibition of photosynthesis in zooxanthellae as these stress conditions damage the photosystem II reaction centres of the zooxanthellae [3]. Bleaching results in varying levels of mortality of the host organism depending on the severity of stress [5].

Field level detection of coral bleaching often gets complicated by various physiological (e.g. in case of coral diseases) and physical/environmental factors (like turbid water) at colony level. Semi-quantitative data provided by refined colour scales like the Coral Health Chart developed by the CoralWatch programme [6, 7] are considered useful for a synoptic description of colony-scale bleaching status during rapid field surveys. The Coral Health Chart serves as a unique utility tool to document the colour transformation of corals over six colour stages during a bleaching condition when the coral loses its own colour saturation and the whiteness/brightness increases due to the loss of zooxanthellae and their pigments [6]. The chart helps in identifying and monitoring the coral health condition based on corals' apparent colour and thus provides a quick, inexpensive and non-invasive way of spot sampling. However, the utility of the Coral Health Chart gets limited if one wishes to understand the pigment level changes that happen in a coral during a bleaching condition.

Field spectroscopy offers an essential support as a non-invasive, proximal remote sensing sampling technique for hyperspectral characterization of sessile, benthic substrates like corals. Field spectroscopy involves the study of interrelationships between the spectral characteristics of objects and their biophysical attributes in the field environment [8]. Spectroscopy involves the collection and characterization of continuous spectra acquired in laboratory (reflectance), in situ with portable and waterproof radiometers (radiance reflectance) and even by remote sensing (remote sensing reflectance). The spectra are analysed in terms of intensities and shapes according to the absorption features characteristic of pigment compounds of the targets.

Few studies have demonstrated the spectral differences that exist between healthy and bleached corals based on in situ hyperspectral signatures [5]. In one of the pioneering attempts, Holden and LeDrew [9, 10] demonstrated that

hyperspectral signature of bleached corals (in 400–700 nm) is significantly different than that of healthy corals sampled from a protected lagoon in Fiji in the South Pacific and from a beach location in Indonesia. They used clustering and ordination analyses along with derivative spectroscopy to discriminate the reflectance spectra of healthy and bleached corals. Clark et al. [11] further investigated the spectral distinction of live and dead corals (in 400–750 nm) at various stages of mortality and algal colonization as sampled from Rangiroa atoll, French Polynesia, soon after the mass coral bleaching of 1998. Their field experiment revealed that recently, dead corals had a relatively pronounced peak around 550–600 nm, and the degree of sharpness or peakedness around 550 nm was used to discriminate live coral from the dead with an accuracy of 88%. However, they also pointed out that efficacy of spectral discriminators does vary at different water depths due to water column attenuation. Another study [12] detected negative shift of the red edge in the reflectance spectra of experimentally stressed and naturally bleached corals. These studies recommended derivative spectroscopy as a promising tool for spectral discrimination of bleached and healthy corals through proximal remote sensing and even later from airborne or space-borne remote sensing data. Accordingly, comparison of in situ spectral characteristics of healthy and bleached corals becomes a prerequisite to develop an understanding on the spectral behaviour of bleached corals.

In this direction, a case study was carried out on spectral discrimination of in situ hyperspectral signatures of live and bleached corals collected from a single colony of *Turbinaria peltata* (Esper, 1794) sampled from Laku Point reef of Poshitra in Gulf of Kachchh during March 2011.

2. Sampling site for field experiment

The sampling site for this particular study, i.e. Laku Point reef (**Figure 1**), is located in the coastal village of Poshitra situated in the Okhamandal region of Gulf of Kachchh in Devbhoomi Dwarka district in Gujarat state of India [5]. Coral reefs, mangroves and rocky shores are major habitats of this site [13]. This is a narrow fringing reef connected to the mainland coast. The coastline is indented with small embayments, 1–2 km long and 0.5–1 km wide [14]. This site is marked with 100-m-wide eulittoral fringing reefs having high coral diversity [15]. Coral colonies grow in shallow, rock pools in the upper eulittoral zone. The rocky pools are covered by barnacles and oysters and produce a rugged topography. These rock pools are found in vertical tiers and exhibit variation to coral distribution and diversity according to tidal exposure. Laku Point site represents prominent biokarst landscape with vertical pinnacles or coastal lapies and pits or pools on the beach rock surface similar to landscapes reported from the Dwarka coast [16]. The common coral genera reported earlier from this site include *Turbinaria*, *Montipora*, *Favia*, *Favites*, *Porites*, *Goniopora* and *Goniastrea* covering 45% of the reef area [14].

3. Field experiment and data processing

The field experiment for the above-mentioned site was meticulously planned with reference to the Survey of India (SOI) tide table information considering Okha (22°58' N, 70°27' E) as the reference tidal station. Laku Point reef in Poshitra was sampled during 20–24 March 2011. The maximum negative tide was –0.09 m on 22 March 2011 [17]. The equinoctial spring tide windows in a year offer suitable conditions for passive, proximal sensing of corals with minimal water column as the

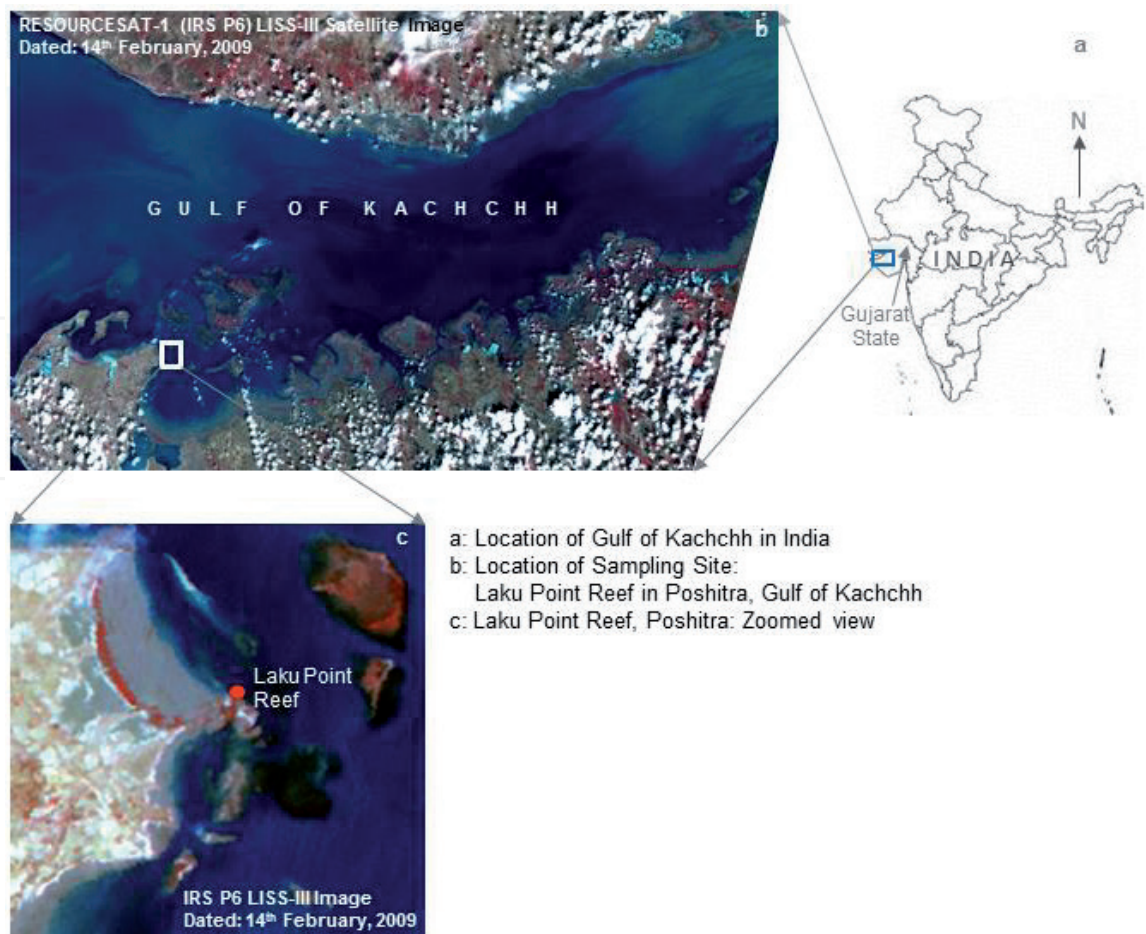


Figure 1.

Location of the sampling site: Laku Point Reef, India ((a) location of gulf of Kachchh in India, (b) location of Laku Point reef in gulf of Kachchh, (c) Laku Point reef, zoomed view from Indian remote sensing satellite).

low tide exposures of reefs coincide with early hours of local day time (i.e. 09:00–11:00 hours) with clear sky conditions [5, 18, 19]. Reflectance spectra of the sampled hard coral were collected with analytical spectral devices (ASD) FieldSpec®3 spectroradiometer having a spectral range of 350–2500 nm and spectral resolution of 3 nm (at 700 nm) and 10 nm (at 1400 and 2100 nm) [20]. The sampling interval is 1.4 nm for 350–1000 nm spectral region and 2 nm for 1000–2500 nm. The visible and near-infrared (VNIR) spectral region (350–1000 nm) in this spectrometer is configured with 512 element silicon photodiode array, while SWIR1 (shortwave infrared: 1000–1830 nm) and SWIR2 (1830–2500 nm) spectral regions are configured with indium gallium arsenide (InGaAs) detectors. The fibre-optic probe has a field of view (FOV) of 25° full conical angle. The spectra were measured holding the optical probe at a minimum height of 30 cm above the target with a nadir view, and due care was taken to ensure that the target diameter was always greater than 15 cm. The field spectroradiometer was calibrated with reference to a Spectralon white plate (or 100% white reference standard), and thereafter multiple spectra were recorded for different sample surfaces, i.e. apparently healthy, partially bleached and bleached (**Figure 2**).

Turbinaria peltata (Esper, 1794) is a representative of *Dendrophylliidae* family (Gray, 1847) of scleractinian corals. This species occurs as flat, plate surface colonies in grey to brown colour. *T. peltata* grows in the rocky foreshores and shallow reef slope zones even in turbid water [15, 21].

The *Turbinaria peltata* (Esper, 1794) coral colony sampled (**Figure 3A and B**) had three representative surfaces: (i) apparently healthy, live coral cover, (ii) partially bleached surface and (iii) bleached surface. This distinction was made in field with

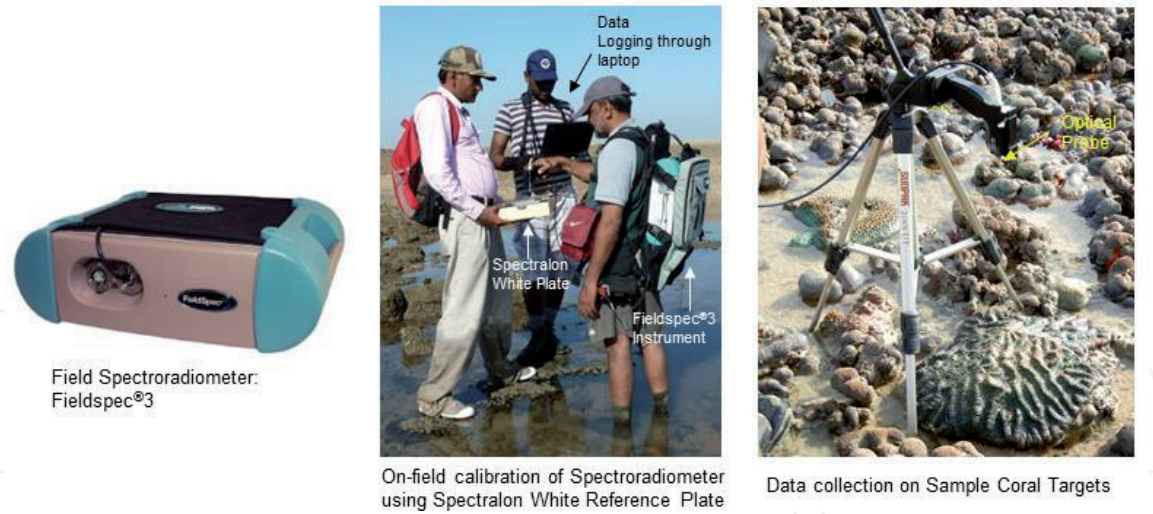


Figure 2.
Field spectroradiometer and in situ hyperspectral data collection at Laku Point reef site, India [5].

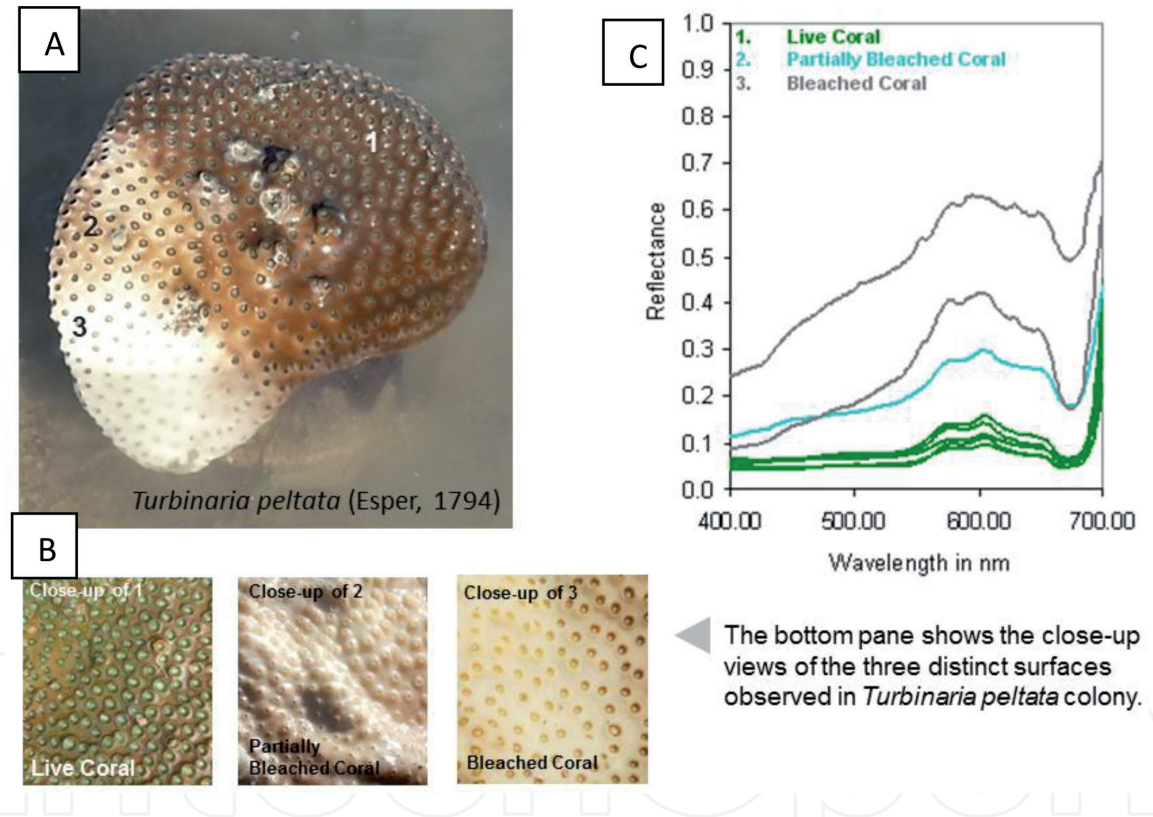


Figure 3.
In situ reflectance spectra of coral species: *Turbinaria peltata* in live, partially bleached and bleached condition (the MRS in each class represents the number of sample spectral measurements for three different surface conditions in the coral colony, e.g. (i) live coral = 5, (ii) partially bleached = 1 and (iii) bleached = 2) [5].

reference to colour differences perceivable to human eye during field sampling. In situ reflectance spectra were collected from each of these surfaces. For each sample surface, a minimum of 30 reflectance spectra were logged with the help of spectra acquisition software: RS3. Field photographs of the sample surfaces were also taken with a digital camera and sequentially numbered. Data logging was completed within a 15-minute period for each sample surface. The field spectra were subsequently processed with the help of ViewSpec Pro software (version 5.6).

The mean representative spectrum ((MRS) and $n = 30$) of these three surfaces was first plotted (**Figure 4**) for the visible region, i.e. 400–700 nm range for visual comparison. It was found that beyond 715–1350 nm, bleached coral spectra closely

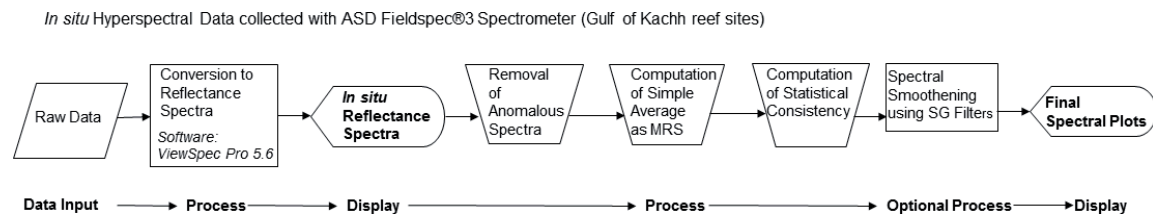


Figure 4.
Flow chart showing *in situ* hyperspectral data processing [5].

follow the trend of the live corals with only local shoulders and troughs getting vertically pronounced [18].

For each sample surfaces, *in situ* reflectance spectra ($n = 30$) were first plotted for visual appreciation and data editing. Anomalous spectra matching neither in magnitude nor with respect to the shape of the rest of the spectra were first manually removed. The remaining spectra were arithmetically averaged to obtain the simple average spectra or the mean representative spectrum (**Figure 4**) for the corresponding sample surfaces. The consistency of the spectral measurements was computed on the basis of the number of spectra falling within ± 1 standard deviation of the MRS [5]. Spectral smoothing was carried out on MRS for noise removal using low-pass, Savitzky-Golay filters whenever required.

4. Spectral discrimination of live and bleached corals

Reflectance spectra or spectral signatures (i.e. reflected light as a function of wavelength) of live corals are considered as a fundamental parameter in reef remote sensing [22] as it is the key determinant of coral cover and coral health. *In situ* hyperspectral signatures are commonly analysed with respect to ‘wavelength feature’ approaches (i.e. spectral feature like reflectance peaks and absorption dips) where the feature is explained with the help of established knowledge on the spectral properties of the constituent materials of the target [23]. In case of a biotic, benthic substrate like corals, reflectance is a complex function of pigments, structure and morphology. The spectral characteristics of corals get determined by pigments from three different sources: (i) zooxanthellae pigments, (ii) pigments present in the ectodermal and endodermal tissues of host coral polyp and (iii) coral skeletal pigments for some species [24]. In case of *in situ* hyperspectral measurements, the physical distribution of pigments combined with the colony morphology of corals will affect the spectral signal received from it [24].

The live corals sampled showed a flattened response between 400 and 550 nm (**Figure 3C**) due to the contribution of strong absorption by characteristic zooxanthellae pigment called peridinin. All these live corals show triple peaks (i.e. local maxima or shoulders) at 575, 600 and 650 nm. This characteristic triple-peaked reflectance pattern was first reported in [25] and is known as ‘brown mode of coral reflectance’ [22]. This spectral pattern is commonly expressed by corals which visually appear in brown, red, orange, yellow or in green colours and is hence called as brown coral mode [22]. The 575 nm peak is known to be a contribution from coral-host fluorescence [22, 26] or more specifically cited as a signature of phycoerythrin (a photosynthetic accessory pigment found in red algae) fluorescence [24, 25]. *Turbinaria peltata* records this peak with a shift of 5 nm at 580 nm. Signature of phycoerythrin fluorescence at 575 nm leads to the circumstantial evidence towards the presence of this particular pigment; however, the same has yet not been concretely demonstrated for corals [24]. The second peak of 600 nm appears with a 5 nm positive shift for the sampled corals at 605 nm. The characteristic third

peak occurs at 650 nm which is 'more of a shoulder than a peak' [22]. Generally, the second characteristic peak occurring at 605 nm dominates the other two peaks in terms of reflectance magnitude following the conventional trend reported globally. The intermittent depression or slight absorption feature located around 590 nm can be attributed to a shifted phycoerythrin absorption reported at 570–579 nm window [27]. All the sampled live corals showed characteristic chlorophyll absorption feature in 670–675 nm window followed by a steep red edge beyond 680 nm. These characteristic chlorophyll absorption and deep red fluorescence beyond 680 nm are attributed to endosymbiont zooxanthellar chlorophyll contribution [22, 24].

The partially bleached and bleached coral spectra in the visible region (**Figure 3C**) differ considerably from the live coral spectra in terms of their magnitude rather than the spectral shape. The partially bleached coral spectrum matches the spectral shape of the live corals with the characteristic triple-peaked pattern but steadily rises in terms of magnitude, almost double the values or more, at specific wavelengths (e.g. at 590–610 nm). Considering the topmost spectral plot as the upper limit of spectral profile of the sampled bleached coral surface, it can be commented that in terms of magnitude, the bleached coral spectrum is characteristically different than that of its live counterparts. The reflectance value of the bleached coral shoots to its maximum at 590 nm, six times as that of live coral. The bleached coral spectra rise steadily in the visible region with minor breaks of slopes located at 426, 505, 545, 556, 558, 578, 586 and 590 nm. The bleached coral spectra also show a stepped pattern of descent with breaks of slopes located at 605, 623, 628, 644, 648 and 657 nm. Thereafter it plunges down to the chlorophyll absorption trough located at 675 nm. Another prominent feature in the bleached coral spectra is the loss of the characteristic first peak, i.e. 575 nm peak, as compared to the second peak, i.e. at 600 nm. Earlier observation [10] on bleached coral spectra to be higher than that of live corals and appearing spectrally similar to bright white coralline sand holds true with these spectra too.

5. Derivative analysis

Derivative analysis is a potential tool for spectral characterization and feature discrimination in the domain of hyperspectral remote sensing. Derivatives of an original reflectance spectrum are numerically computed with respect to the wavelengths. First, second- and higher-order derivatives allow the identification of exact wavelength(s) at which the inflexion points and absorption troughs are located in the original spectrum [28]. Derivatives can resolve overlapping absorption features embedded within the zero-order spectrum. Since the late 1990s, derivatives have been applied in hyperspectral remote sensing of coral reefs. Holden and LeDrew used the first and second derivatives of in situ reflectance spectra for the identification of wavelength-specific characteristics of coral reef substrates [9]. They suggested that the first derivative spectra can be reliable means to distinguish healthy and non-healthy coral.

The first (**Figure 5**) and second derivatives (**Figure 6**) of the zero-order spectra of healthy and bleached surfaces of the sampled *Turbinaria peltata* were numerically calculated over 4 nm as finite band resolution to exaggerate the spectral shapes and enhance the subtle features [5, 19]. Derivatives are computed by dividing the difference between successive spectral values by the wavelength interval separating them [9]. This method gives the approximation of the first derivative at the midpoint of the spectral values. The rate of change in reflectance (or the slope) with respect to wavelength is represented by the first derivative spectra, while the second-order derivatives exhibit the change in slope with respect to wavelength. The

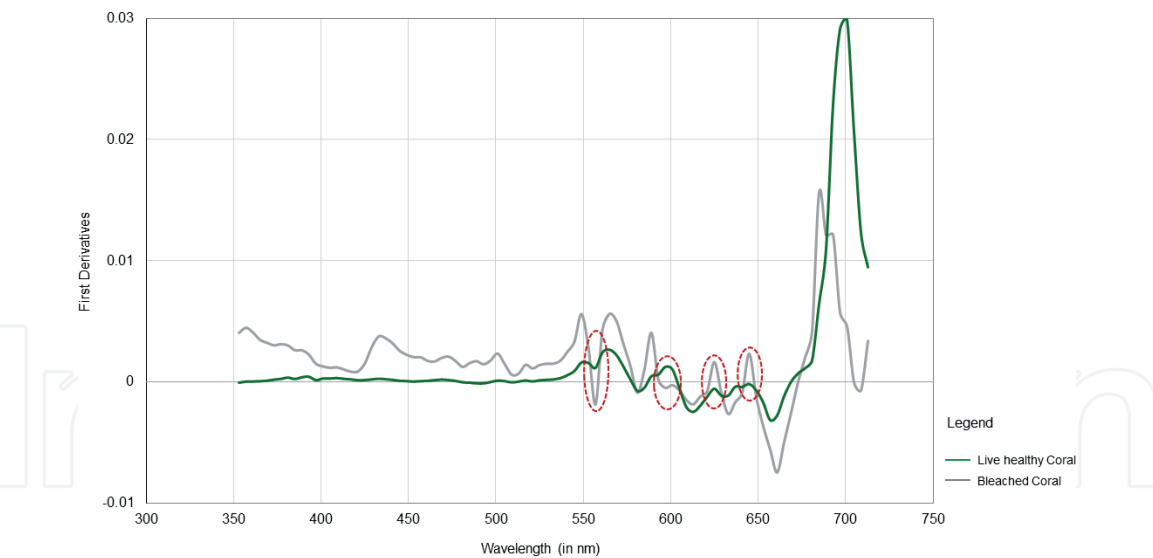


Figure 5. First derivatives of sampled live and bleached corals (red dashed circles indicate the zones of slope differences in the derivative spectra) [5].

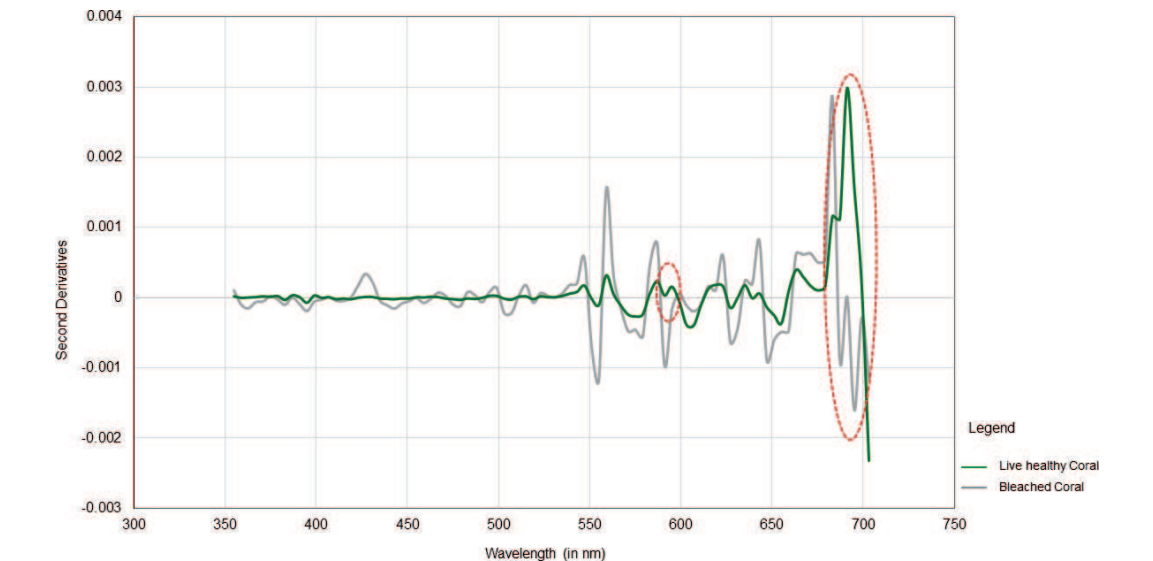


Figure 6. Second derivatives of sampled live and bleached corals (red dashed circles indicate the zones of slope differences in the derivative spectra) [5].

first derivative spectra are considered as reliable means for spectral discrimination as they are less function of noise as compared to the second derivative spectra [5, 9, 19].

The first derivatives of sampled live and bleached coral spectra (**Figure 5**) reaffirm the magnitude difference in reflectance values in the UV-visible region (i.e. 350–550 nm). At 557 nm and at the narrow window of 593–605 nm, the first derivatives of the live and apparently healthy corals record a positive slope, while the bleached corals record negative slopes. This trend is reversed at 625 and 645 nm when the first derivatives of bleached corals record a positive slope and that of the live ones record negative slopes. The window of 593–605 nm corresponds with the observation as reported earlier [11], and it is recommended to use 596 nm (i.e. the midpoint of this window) as a slope gradient discriminator to distinguish live, recently dead and bleached corals with high accuracy. The second derivatives (**Figure 6**) of the sampled live and bleached coral spectra identify two prominent zones of slope differences, i.e. 591–599 and 687–703 nm. In both these windows, the live corals record positive second derivative values, while the bleached ones have negative values.

6. Conclusion

As observed in this study, live and bleached corals get distinguished in the visible region over 500–600 nm. The first derivatives discriminate live and bleached corals at 557, 625 and 645 nm channels and also in the spectral window of 593–605 nm. The second derivatives separate live and bleached corals in two narrow spectral windows: 591–599 and 687–703 nm.

Wavelength-specific spectral discrimination of live and bleached coral spectra using derivatives, however, needs more number of in situ data samples collected from different coral species. The onset of mass coral bleaching events can provide such ideal real-time field conditions facilitating collection of this kind of species-specific in situ reflectance data of both live and bleached corals. Field spectroscopy is a potential non-invasive tool to provide first-hand information on the health or ecological status of the corals with reference to pigment level changes at organism or colony level.

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