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Sources of errors in the measurements of underwater profiling radiometer

Noah Silveira[1], T. Suresh[1], Madhubala Talaulikar[1], Elgar Desa[2], S.G. Prabhu Matondkar[1] & Aneesh Lotlikar[2]

[1]National Institute of Oceanography, Dona-Paula Goa, India
[2] Indian National Centre for Ocean Information and Services, Hyderabad, India
[E-mail: 87.noah@gmail.com]

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There are various sources of errors from the measurements of optical parameters using a radiometer, which can be classified as mode of deployment, instrument and environment. The errors from the deployment are primarily from the ship and superstructure shadows. Instrument could be a source of error arising from its self-shadow, drift in the calibration and temperature effects. There could be large errors, which at times may be unavoidable to environment factors such as wave focusing at the surface layers, sea state conditions which may affect the tilt of the instrument, atmospheric conditions such as cloud cover, solar elevation, wind and rain. Radiometric optical data in water could also get affected due to Raman scattering and fluorescence effects. Here we discuss the above sources of errors and how they could be minimized. From the measurements carried out in the coastal waters off Goa and Arabian Sea using the hype-spectral radiometer, we propose simple protocol to measure the data and also screen the erroneous data measured from the radiometer.

[**Keywords:** Scattering, Accuracy, Error]

Introduction

One of the primary objectives of the radiometric measurements of underwater light for ocean color applications is to measure and derive spectral waterleaving radiance, $L_w(\lambda)$ with least uncertainty and high accuracy under all conditions. The acceptable uncertainty in $L_w(\lambda)$ is less than 5% for satellite validation[1]. In order to achieve the desired accuracy we need to have better understanding of the sources of errors from the measurements using radiometer and evolve solutions to avoid them.

There are two types of radiometers used to measure light parameters of the ocean, one that measure above the water and the other inside the water. The radiometers used for the above water measurements, provide only surface optical parameters. Ship perturbations, sun glint and superstructure are the source of errors for such above water measurements. Considering all mentioned sources of errors, a free falling profiling underwater light-measuring radiometer was developed that could minimize such errors to a great extent[2-3]. Profiling instruments were earlier deployed using hydrowire, which gave errors from ship perturbations and superstructure and non-uniform descent rates[1]. As a solution to this the instrument was deployed from a boom extending out in the sea from the platform[4]. Cranes and boom cause additional shadows, they cannot extend beyond their limit to avoid ship shadows and since they are on the ship, pitch and roll can hamper proper deployment and measurements. Winch operations also take considerably more effort and time to complete the operations. The profiling instrument deployed on a taut wire from a moored weight at the bottom resulted in uniform tilt and velocity of the instrument. The *in-water* profiling radiometers using latter modes of deployment suffered from the shading effect of the platforms[1,5-6]. Most of the profiling radiometers were tethered with a reinforced cable that carries the power and data, which was avoided in a self-recording hyperspectral radiometer[7]. Though the source of errors is known, quantifying them and understanding their behaviour will permit protocol to process the radiometric data and derive optical parameters with fewer errors and with required accuracy.

Materials and Methods

In order to meet the stringent quality requirements of marine optical data for satellite ocean color sensor validation, development of algorithms and other related applications, it is very essential to take great care while measuring these parameters. There are two prime

Table 1–Errors and their corresponding remedial action

Sr. no	Errors	Remedial action
1	Ship and superstructure shadows	Deploy the radiometer far from the research vessel
2	Wave focusing-defocusing	-
3	Self-shadowing of the instrument	Design of the radiometer and avoid any additional attachments
4	Reference Irradiance Sensor	Mount it at the highest point. Mount on 'gimbal' to avoid tilt
5	Tilt of the radiometer	Proper release mechanism during deployment
6	Zero depth offset	Do pressure tare on deck just before immersing the radiometer in the water.
7	Cloud patches	Avoid cloud patches and measure during uniform sky conditions
8	Temperature correction	Need correction for the sensor variability due to temperature

sources of errors from the measurements of optical parameters using a radiometer that has been studied extensively, one from the ship or super structure as ship shadow and ship perturbation and the other arising from the effect of wave focusing-defocusing. The additional sources of errors arise from self-shading of the instrument[5,8-9], intermittent cloud patches during measurements, depth offset adjustment to determine the exact surface depth, mounting of the reference solar irradiance sensor, tilt of the instrument with respect to the vertical, and correction due to temperature variations and dark values. (See Table 1).

We present here the results of our study on the errors arising from the measurement using the profiling hyperspectral radiometer, suggestions on measurements methods to minimize errors and methods to detect and weed out errors from measured data.

Results and Discussion

Hyperspectral radiometer

The instrument used for measuring underwater light parameters is a free falling hyperspectral radiometer, HyperOCR (Satlantic Inc, Canada, http://www.satlantic.com). (Fig.1). The instrument has a 'T' shaped design with two optical sensors mounted apart on the same horizontal plane on this metal frame. The middle of the 'T' section is cylindrical and the bottom is a parabolic nose cone with adjustable ballast weights just above the nose cone. The instrument has fins in the upper section, which provide balance and allow profiling in water during free fall with very low tilt. The free-fall descent rate of the instrument is user-adjustable using appropriate lead weights near the nose cone from 0.1 m/sec to 1.0 m/sec in Case-1 waters and a relatively lower descend rate of 0.1 to 0.3 m/sec recommended for case-2 waters. The lower portion of the cylindrical tube with nose cone houses the tilt and pressure sensors, while the upper portion has the temperature and conductivity sensors and electronics and connector for the tethered telemetry cable. The instrument is lowered with this tethered cable, without any external winch wire. In the profile mode of operation, the instrument being lightweight is deployed in "fish out" mode away from the ship, avoiding any ship shadow by a single operator. The reinforced cable carries the power and data to the deck unit and the data is acquired on a computer. The commonly used hyperspectral optical sensors are irradiance and radiance and have a spectral range of

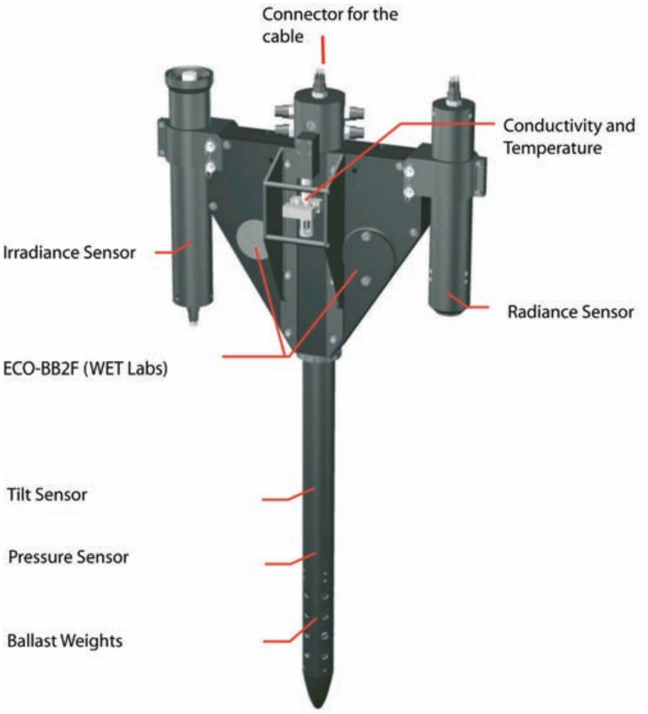

Fig. 1–Hyperspectral Radiometer

350-800 nm. The irradiance sensor measures the downwelling irradiance while the radiance sensor is used to measure the upwelling radiance.

Measurement errors

Ship Shadow

There have been elaborate studies carried-out on the effect of ship shadow affects the optical measurements[8,6,10]. The problem of shadow is an inherent problem of in-water upwelling radiance and irradiance measurements. Since every photon of upwelling radiance (assuming no light sources in the water volume) must have passed the instrument depth on the way down to come back from beneath, it is obvious that some of them are blocked by the instruments housing or other man-made objects (buoys, platforms, ships).

The Monte-Carlo simulations by Gordon (1985) indicate that the error in downwelling irradiance rarely exceeds 2% as long as skies are clear and the sun is within 45 degrees of the stern. However at low solar elevations, these errors can increase to about 10%[8] also shows that the errors are reduced as the instrument is moved horizontally away from the ship although errors during diffuse light conditions may remain as high as 30%[11].

Effect of ship shadow can be minimised by deploying the instrument away from ship. The general equation for distance away from ship, d in meters, is given as a function of diffuse attenuation K_d [12]

$$d = \frac{\sin(48.4^0)}{K_d}$$

In the Arabian Sea, the average value of K_d at 490 nm is found to be 0.1 and hence most of the operations were carried-out with radiometer at least 10 meters away from the boat or ship.

We positioned the boat to keep the radiometer well under the sun, with bow-stern perpendicular to the position of sun, wind blowing towards the side of deployment, allowing the ship or boat to drift away from the radiometer, so that it does not come under the shadow after it is deployed. (Fig. 2). Most of the measurements are taken at noon with low zenith angle. In the Arabian Sea, when the instrument was hauled up after every cast, the instrument often surfaced far away (~50 m) from the ship due to the currents. After the cast, when it is brought up with the help of the tethered cable, the turbulence at the surface due to waves, does not allow the radiometer to be in vertical position even when the cable is kept slightly slack. This drag keeps the radiometer incline to the vertical and close to the surface.

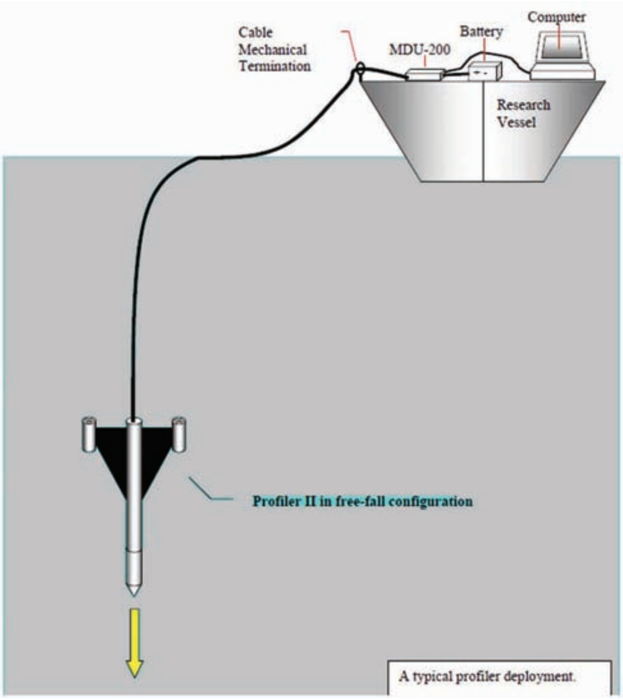

Fig. 2–Deployment of Radiometer

There is a striking difference between shadow casts and sunny casts for the shadow casts and the sunny casts. The surface values of apparent optical properties are largely affected by the ship shadow and among these the upwelling radiances, $L_u(\lambda)$ and $L_w(\lambda)$, are more affected than the other apparent optical properties such as downwelling solar irradiance, $E_d(\lambda)$ and diffuse attenuation coefficient, $K_d(\lambda)$[11,6]. Large waves have some effect on clear waters with low $K_d(\lambda)$ values[5]. Though $L_u(\lambda)$ and $E_d(\lambda)$ may be susceptible to ship shadow, their ratio, remote sensing reflectance $R_{rs}(\lambda)$ seems to be less susceptible to the ship shadow effects. The variations in $L_u(\lambda)$ are found to vary spectrally with low differences at lower wavelengths and increase towards higher wavelengths[11]. We see similar trend in the $R_{rs}(\lambda)$ data. Though the data below 600 nm for the cast under the shadow of the boat and under the sun seem similar, the variations are distinct in the longer wavelengths above 600 nm. (Fig. 2). The values of $R_{rs}(\lambda)$ derived using the solar irradiance from the reference sensor $E_s(\lambda)$, are much higher for the measurements under the sun as compared to measurements in the shadow. (Fig. 3).The errors due to ship shadow are relatively larger under overcast skies as compared to clear skies[6,8,10].

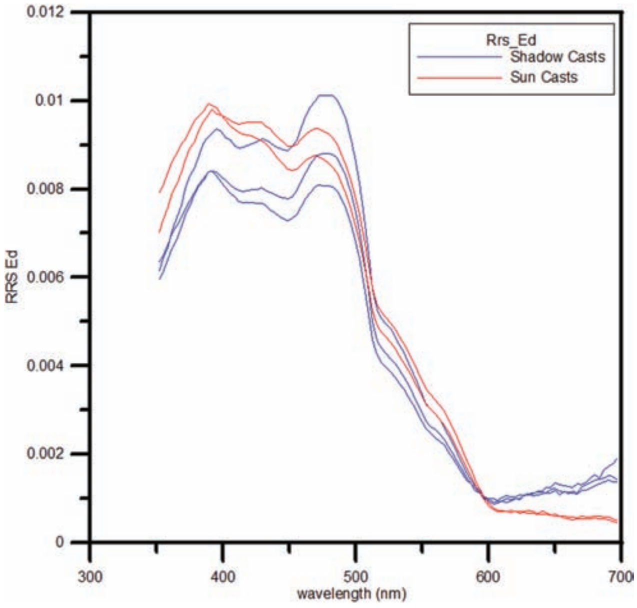

Fig. 3–Rrs(λ) derived using the Ed(λ) for the measurements in shadow of the boat and under the sun.

Wave focussing

Waves can cause a significant effect on the radiance measurement using the radiometer. Accumulated light beams can penetrate deeper and can deliver punctual higher intensity into water. The shape of the water surface specifies the light intensity distribution in the water column in which the radiometer is deployed. With increase in depth, light fields smear because of scattering and overlaying of diverse developed focal depth. The light regime in between 3 m to 25 m of water column is affected by large scale surface structures.

Even waves with small amplitudes have a significant effect on the redistribution of irradiance. Current commercially available irradiance sensors typically drop at 0.8 m/s and sample at 8 Hz. Because of the statistical nature of the sea surface and the discrete sampling of the irradiance field, it is to be expected that no two irradiance profiles will be the same, even though the wind speed and IOP's (Inherent Optical Properties) are constant.

This effect usually cannot be stopped, but can be compensated[13-15].

Self shadow of the instrument

The profiling radiometer HyperOCR is slim and probably has less self-shadowing, however the floating collar when the instrument is deployed in float mode could add to this effect. Since the instrument is free falling and not attached to any frame or cage, the self-shadowing is less. The radiometers are designed to reduce the effect of the instrument itself providing shadow on the sensor. Instrument self-shading, for example, can increase measurement uncertainty from a few percent to several tens percent as a function of wavelength, instrument radius, and illumination conditions[8].

Reference sensor

The solar irradiance measured at the surface of water is used as a reference to compute remote sensing reflectance of the surface.

The reference that measure the solar irradiance falling at the surface and is used to derive the remote sensing reflectance, $R_{rs}(\lambda)$ needs to be held upright with zero degree of tilt, to avoid measuring solar irradiance at an inclined plane. This demands that the platform such as boat or ship be steady without roll or pitch, which is unavoidable on boats. However such dependencies can be avoided by mounting the sensor in a 'gimbal' frame. The reference sensor also needs to be mounted at the highest point, avoiding shadows from structures and fumes from the boat or ship.

Cloud patches

The optical parameters need to be measured under uniform sky conditions all through the measurements and thus avoiding cloud patches.

Tilt of the radiometer

Most of the studies of the free falling bodies have been studied in calm water conditions with isotropic properties of temperature, salinity and density and for applications related to a study of the trajectories of the mines[16-18] and rheological applications[19-20]. Free falling radiometer is a better solution to determine the in-water optical parameters avoiding ship shadows and operating with ease in short time. Hydrodynamic studies have shown that movement of a falling cylinder in water column is a highly nonlinear process and can have six trajectory patterns such as straight, spiral, ûip, at, seesaw and combinations of these. Such studies indicate that the trajectories of a rigid cylinder depend on the distance of centre of mass and centre of geometry, drop angle and aspect ratio (length to diameter ratio), initial velocity and physical parameters of the cylinder[19,18]. The orientation of a falling cylinder with respect to the vertical or direction of fall, known as shape-tilting, is proportional to the aspect ratio (length to diameter) and all rigid bodies have a tendency to fall in the direction of gravity along their long axis. The tilt is sensitive to aspect ratio and increases with aspect ratio[20,16,19].

The HyperOCR radiometer is a perfectly designed body with low aspect ratio and the centre of mass is away from the geometric centre or centre of volume, which provides large restoring moment thus enabling vertical trajectories with low tilt. (Fig. 1).

Our studies have shown that the tilts of the radiometer are observed near the surface and at depths.

The tilt of the radiometer at the surface is attributed to environmental parameters such as wind and waves. Being a free falling instrument, the radiometer is deployed when required by releasing the cable. Under this condition, the radiometer often commences the dives from an inclined plane and attains the vertical position with low orientation after having traversed through some depths during this period. (Fig. 5). Thus the data from the radiometer is tainted with large tilt angles from the surface to a few meters below. The radiometer thereafter maintains low tilt as it descends vertically. Since data beyond the tolerance limit of tilt, which is taken as 5 degrees, is discarded during post processing, we often miss critical data from the surface layer. As observed from the experience of deploying the free falling radiometer, this seems to be an inherent drawback, a price that needs to be paid for avoiding the ship shadow.

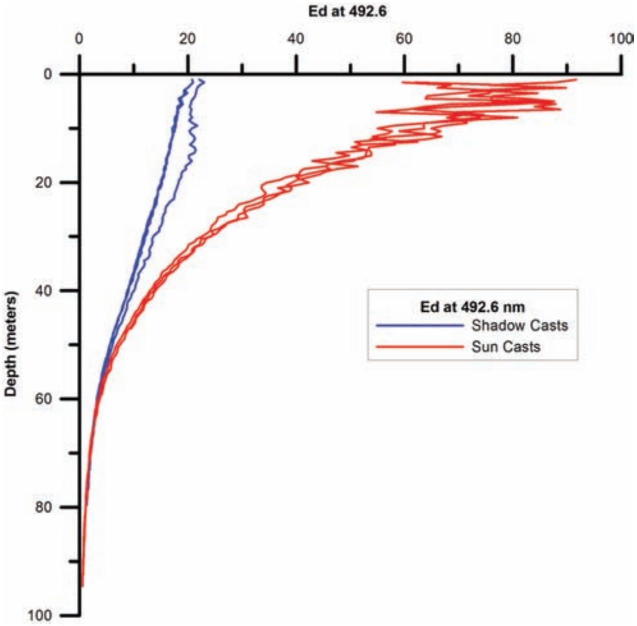

Fig. 5–Downwelling radiance vs Depth of sunlight and shadow casts

To minimize this effect in the initial stages, an extended boom with pulley arrangement and a pelican release hook arrangement was used for the trial. The boom extended to about 2 m from the boat and was placed firmly at the gunwale of the boat. The pelican hook was hung over the water with a rope going over the pulley whose other end over the pulley was held firm. The radiometer was hung from the pelican hook. Pulling the lever vertical by a thin rope fastened to it from the boat operates the pelican hook release mechanism and releases the radiometer in water. The radiometer is positioned just above the water and it stays vertical. Assuming that the pressure sensor does not always give the correct depth at the surface, pressure tare to determine the depth offset and get the right depth from the surface is performed after adjusting the height of radiometer to be just above water, hence there is less ambiguity in determining the depth from the surface. The tethered radiometer cable is held loose on the deck of the boat before deployment. Thereafter the data logging starts and the radiometer is released from the hook by pulling the lever of the pelican hook. The radiometer dives vertically and the cable is paid out with less tension, keeping in tandem with the descent of the radiometer while taking care to release only the required amount of cable. The operation of the release mechanism lever does not demand any effort and the radiometer can be deployed with ease. After the radiometer reaches the required depth of at least 1% of light level, radiometer is hauled up with the reinforced cable of the radiometer and readied for the next cast.

The disadvantage of this method is that it suffers from the shadow of the boat and boom. Extending the boom up to 10 m and keeping the structure very narrow can circumvent the problem of ship shadow. We had a trial using the boom and pelican hook under very rough conditions at the mouth of the Zuari estuary, Goa, during the monsoon period of July 2010. The results were very encouraging and we were able to get the surface data with less tilt when compared to the conventional “fish out” method of deployment. (Fig. 4).

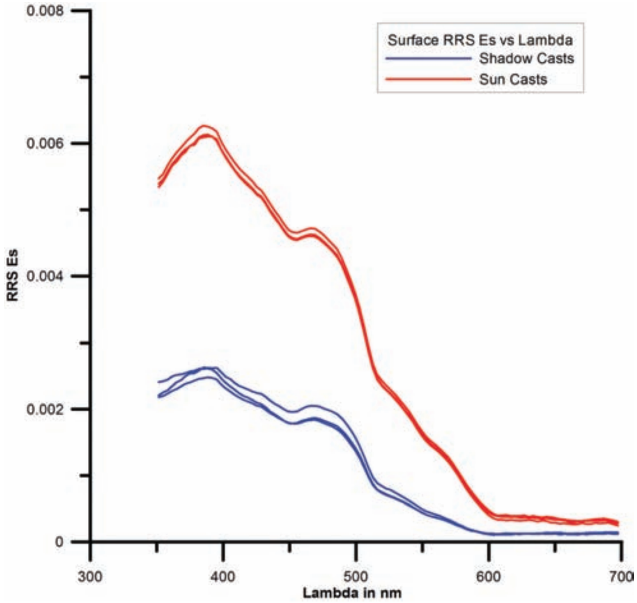

Fig. 4–Rrs(λ) derived using the Es(λ) for the measurements in shadow of the boat and under the sun

The trials have confirmed that the tilt observed in the surface layer is primarily due to mode of deployment and turbulence of water, which does not allow the radiometer to stay vertical during the dive. Hence a method is suggested that will keep the radiometer afloat on the surface of water maintaining vertical position and then releasing the radiometer to dive vertically down. Whatever the method adopted, care should be taken that no shadow is cast over the instrument, with the release being smooth without a jerk so as to allow the instrument to fall freely and descend without appreciable tilt (Fig. 6).

Here we also place some suggestions that could help in improving the performance of the hyperspectral radiometer. We have observed that often after diving through some depth beyond 80 m, there is a large tilt in the instrument. These effects could not be attributed to the change in the density. The plausible reason for this is attributed to the tethered cable, which produces negative buoyancy due to the air trapped in the jacket of the cable. The solution to this problem is do away with tethered cable and a have self-recording feature in the radiometer.[7]. The stability of the radiometer could probably be improved by changing the shape of the nose cone. The radiometer has cone shaped nose ends, and it has been reported that the trajectories also depend on the shape of the cylinder nose ends and blunt shape is found to be hydro dynamically more stable[18] (Fig. 7).

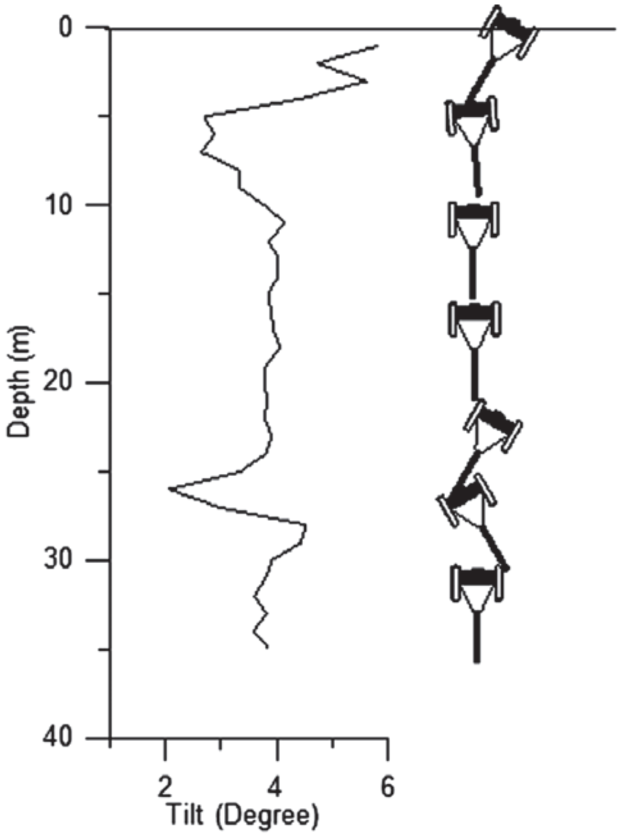

Fig. 6–Depth vs Tilt (schematic)

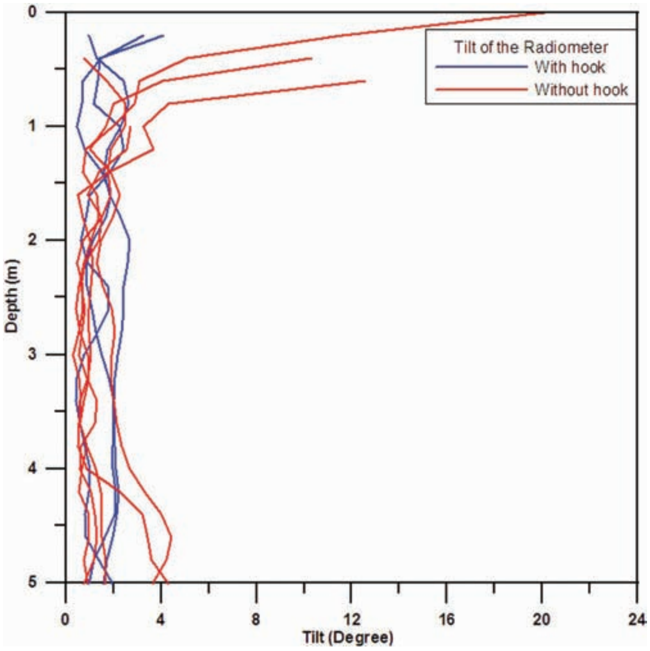

Fig. 7–Test of Tilt with and without the use of Pelican Hook

The tilt at depths away from the surface is attributed to the stratification of water. (Figure. 5). The instrument is found to experience sudden tilt at the stratification layer and then steadies itself and dives further. The tilt at the interface layer cannot be avoided, without compromising with the design of the radiometer and rate of descent.

Zero Depth

Since the surface optical parameters are of prime importance, it essential to ascertain the surface depth or zero depth of the instrument. A pressure tare operation on the instrument on the deck sets the zero depth and the acquisition software and the post processing software use this offset to determine the actual depth (Fig. 8).

QUALITY CHECK

Here we propose simple checks on the radiometer data, which will weed out bad data and allow for quality checks. (See Table 2).

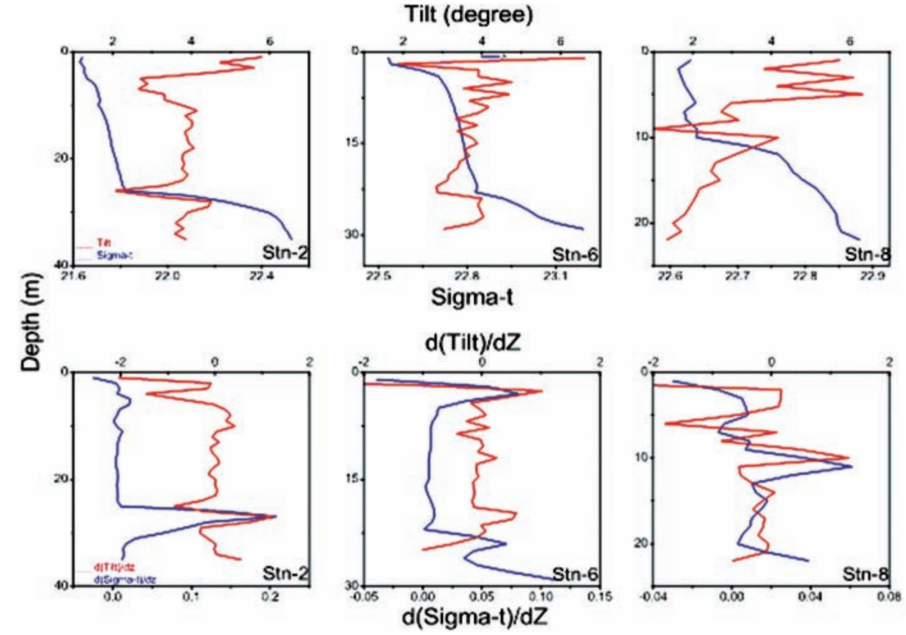

Fig. 8–Tilt due to stratification (Blue density, Sigma-t and red indicate the tilt of the radiometer with respect to the vertical)

Table 1 Simple Tests for good Radiometer Data

1. $K_d(\lambda) > K_w(\lambda)$, where $K_w \sim [aw(\lambda) + bbw(\lambda)]/\mu s$
2. Check for $R_{rs}(\lambda)$, $\lambda > 700$ nm. for $R_{rs}\_E_d$ and $R_{rs}\_E_s$
3. $E_d(\lambda) > F_0(\lambda)$, where $F_0(\lambda)$ is the top of the atmosphere (TOA) solar irradiance
4. $E_s(\lambda) > F_0(\lambda)$
5. $E_d(z, \lambda) <= E_s(\lambda)$
6. $E_d(z, \lambda)$ should decrease exponentially with depth.
7. Check for the surface tilt – if the tilt is less than 5 degree, as the radiometer could have been dropped close to the boat. Check the data for shadow cast.

Conclusion

Under water optical measurements must be carried out with the utmost care and precision. The sources of errors have been described and methods to minimise them are explained. Many errors like self shadowing of the instrument cannot be avoided unless the design of the instrument is altered. The time of taking readings is also very important, since light plays a very important role in underwater optical measurements. Errors are greatly minimised by taking a few precautions into consideration. Ship shadow, tilt and zero depth are the most common sources of error, and these have been explained.

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