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ВЕРИФИКАЦИЯ ВТОРИЧНЫХ ОПТИЧЕСКИХ ХАРАКТЕРИСТИК, ВОССТАНАВЛИВАЕМЫХ ПЛАНЕРАМИ СЛОКАМА

Одно из принципиальных преимуществ планеров – обеспечение ими измерений с высоким разрешением в малых временных и пространственных масштабах. Они автономно работают 24 ч в сутки 7 дней в неделю при любой погоде и любом состоянии моря, увеличивают количество измерений в сутки (судовые измерения обеспечивают 87 профилей в день, а планеры – 665), относительно дешевы, легко перемещаются и, наконец, требуют малых затрат мощности в течение длительного времени. Задачи данного исследования: 1) найти радиометрическую неопределенность измерений нисходящей облученности (E_d) с планера; 2) применить методику подводного дистанционного зондирования для вычисления среднего коэффициента вертикального ослабления K (усредненный по некоторому интервалу глубин от непосредственно под поверхностью до глубины расположения приемника света) на основании подтвержденных данных об измеренных планером E_d; 3) преобразовать средние K в локальные (т.е. в K для малых приращений глубин около 1–2 м), чтобы сгенерировать вертикальный профиль K при различных падающих потоках излучения (различные атмосферные и облачные условия).

Ключевые слова: автономные планеры, подводная облученность, показатель диффузного ослабления.

Slocum Gliders – a slocum glider is long-duration autonomous underwater vehicle manufactured by Webb Research Corporation (http://www.webbresearch.com/). It moves up and down in the water column by changing the buoyancy; using wings and control surfaces to convert the vertical velocity into forward velocity so that it glides downward (dives) when denser than water and glides upward (climbs) when buoyant. The pitch-angle is set in software and adjusted internally by changes in buoyancy and a movable battery pack that shifts the center of gravity with respect to the center of buoyancy. During flight they are continuously executing a dive-and-climb sequence (also called a 'yo'). The optimal dive (or climb) angle is –26 or +26 degrees to the horizontal. The glider surfaces at regular intervals to collect a GPS position, communicate its data to shore via Iridium or Freewave, and download new instructions/missions. The specifications of the Slocum Coastal glider can be found below.

Slocum Coastal Glider Specifications:
size – 52 kg and length – 1.8m;
speed – 0.35 m s^{-1} horizontal and 0.2 m s^{-1} vertical;
range – 25–40 days or 600–1,500 km; Depth – 0–200 m;
energy – C-cell alkaline;
navigation – GPS, dead-reckoning, compass, pressure, transducer and altimeter;
communication – Iridium and RF (Freewave).

Glider Sensors – NURC has seven Slocum gliders that have science-payloads in which a variety of sensors have been installed. All Slocum gliders come with a non-pumped low-drag Sea-Bird CTD (SBE–41). The focus of this study is on the radiometric sensor (Satlantic; OCR–504I), which measure downwelling irradiance (E_d) at four wavelengths (412, 444, 491 and 555 nm). The OCR 500 series radiometers are fully digital optical sensors (multi-spectral radiometers) that have a fully characterized cosine response with low fluorescence filters. Some of the other optical sensors that can be deployed on the gliders are bb3 (a single-angle sensor, 117°, for measuring optical backscattering at 470, 532 and 670 nm [1] by WETLabs, ECO Series), bb2f (the ECO Triplet measures optical backscattering at one wavelength, 532 nm) and chlorophyll and CDOM fluorescence by WetLabs) and BAM (a beam attenuation meter specifically designed for AUVs by WetLabs; 532 nm).

It's important to note that the OCR sensor is a plane radiometer; therefore the best measurements are made when it is parallel to the sea surface. Fig.1 shows a Slocum in at the surface with an *Ed* sensor which has been mounted in a 21° inclination angle. This means that the radiometer was designed for optimal sampling on the up-cast (the climb) direction, as confirmed from fig.2 that represents the downwelling irradiances (log scale) retrieved from a typical virtual mooring glider mission.

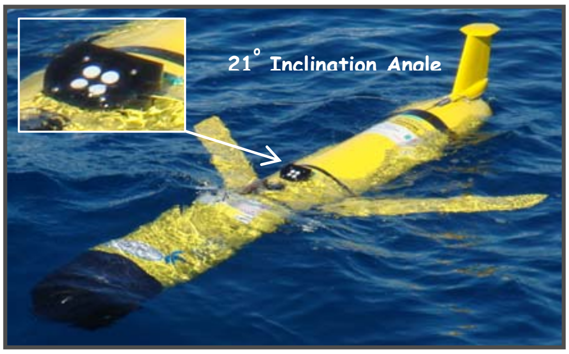

Fig.1. Slocum Coastal Glider equipped with an irradiance sensor (OCR-504I).

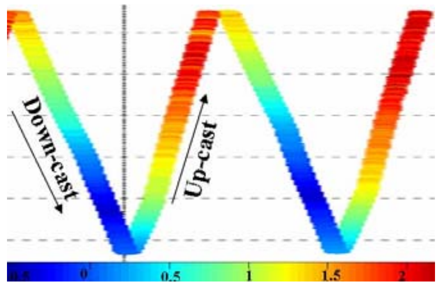

Fig.2. Downwelling irradiance (555 nm) from a virtual mooring glider mission. There is a difference between down- and up-casts due to the sensor orientation.

Submerged Remote Sensing Technique – In the early 1980's a novel approach was proposed at the Visibility Laboratory, Scripps Institution of Oceanography, to separate the transmission/attenuation of the atmosphere from the water component by measuring some E_d at some fixed depth. This was developed under the Submarine Laser Communication (SLC) program and was later named the Submerged Remote Sensing technique [2]. The approach was to make measurements at two wavelengths and use these measurements in a set of equations, which could be solved for the separate attenuations. The technique requires the absolute measurements of E_d at two wavelengths and knowledge of the date, time, location and depth of these measurements. In 2009, the SRS technique was reviewed, implemented and then tested against a much larger optical database [3]. The RMSE difference between the modeled (SRS) and measured mean integrated K (three oceanic basin; n = 1.613) was 0.0063 m^{-1} and these results were very similar to those found [2]. For their study they used irradiance profiles collected in the North Atlantic for depths ranging from 20 to 120 m, $K(490)$ ranging from 0.03 to 0.4 m^{-1} and atmospheric conditions from 100 % overcast, broken cumulus, haze to clear sky. So the SRS technique calculates mean K $[K_d(\lambda, z) \approx -1/z \ln(E_d(\lambda, z)/E_d(\lambda, 0))]$ without measurement of E_s or the requirement that it remains constant during deployment (estimates of K_{SRS} are not dependent on cloud cover or the angle of incidence on the sensor, glider up- versus down-cast). This makes the SRS technique a very powerful tool for converting downwelling irradiances measured from gliders or towed ve-

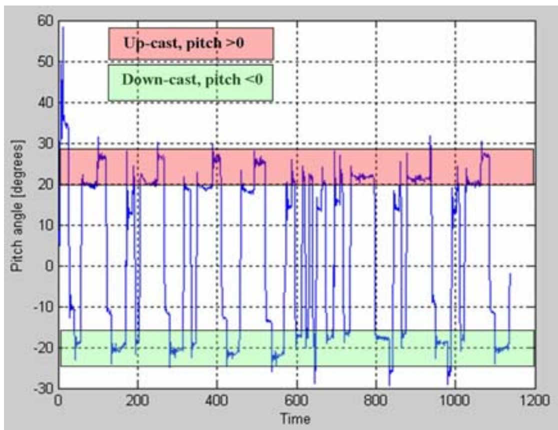

Fig.3. Glider pitch angle as a function of time during the BP'09 cruise in the Ligurian Sea. The red and green shaded areas represent the up- and down-casts. The best time for irradiance measurements is the red shaded area.

hicles to water clarity or diffuse attenuation coefficients.

Methods. Data validation of the absolute downwelling irradiance was performed considering only the up-cast data in which the glider has the proper pitch angle (~26 deg) so that the radiometer is parallel to the sea surface. It's also important to understand some general glider flight characteristics. In particular, one must take into account that, typically, a glider takes about 4–5 minutes to achieve the desired pitch angle (~26 deg), as showed in fig.3, therefore the data close to a glider changing inflection (from down-cast to up-cast, or *vice versa*) cannot be included in the data validation analysis.

To validate E_d measurements made from Slocum gliders, data was selected from two separate gliders (Elettra and Sophie) and compared to data collected from a highly calibrated hyperspectral radiometer (HyperPRO II). The HyperPRO II has a spectral range from 305-1,100 nm, spectral sampling at 3.3 nm pixel^{-1}, spectral accuracy of 0.3 nm, spectral resolution of 10 nm, and stay light of $<1\times10^{-3}$. The cosine response for irradiance is 3 % @ 0–60° and 10 % @ 60–85°. This radiometer is a calibration quality instrument in which stray has been determined and additional calibration procedures performed. For the glider data a virtual mooring mission was programmed so that the glider made multiple up- and down-casts (~20) covering a small horizontal distance (~1 km). These comparisons (fig.4) can be considered reliable if they satisfy the following conditions; 1) the glider and HyperPRO II measurements have to be performed simultaneously (same day and close in time for a similar solar zenith angle); 2) the measurements have to be performed in homogeneous areas; 3) the glider tracks have to be designed so that they can be processed as a single cast like the HyperPRO II profile.

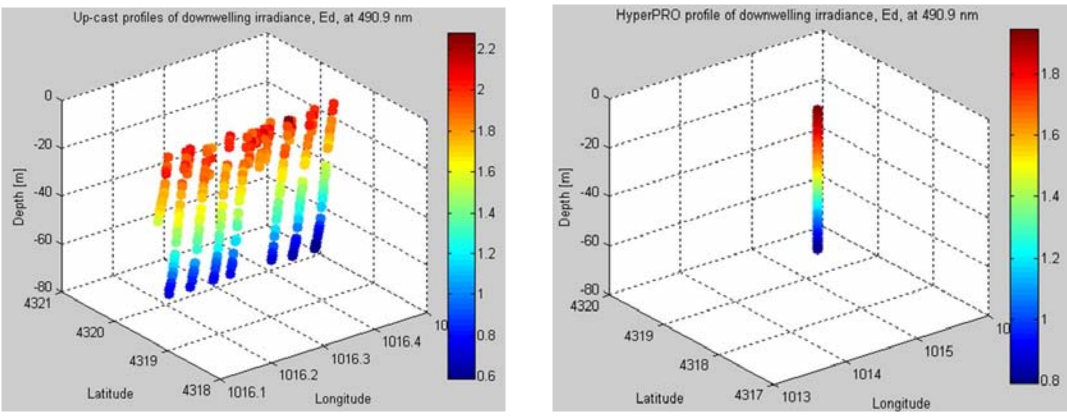

Fig.4. Downwelling irradiance [Ed(491)] from up-casts during a virtual mooring glider mission on 21 Aug 2010 (Left panel; 8.00–13.00 UTC) compared with a HyperPRO II cast (Right panel; ~12:00 UTC in the Ligurian Sea during BP'09 Cr).

Results. Fig.5 shows that with a minimal amount of quality control and quality assurance (QC/QA) validation quality radiometric data [$E_d(\lambda)$] can be obtained from Slocum gliders even though the angle of the E_d sensor changes between up- and down-casts and there might be some stability issues during profiling. The most critical requirement is that the E_d sensors are rigorously calibrated before and after each cruise/deployment.

Most optical sensors on autonomous underwater vehicles, gliders and moorings measure the inherent optical properties (IOPs; absorption, scattering and attenuation) because daytime illumination differences (clouds, aerosols, etc) do not affect IOP measurements as they are directly related to in-water properties. IOPs are also not sensitive to vehicle orientation as AOPs, like E_d. Currently, to calculate the diffuse attenuation coefficient (K) from E_d, the surface irradiance [$E_s(\lambda)$] must be measured, if variable, or remain constant during the deployment of the radiometer. Because of this requirement, the utility of E_d measurements on gliders, which do not have the capability to measure E_s concurrently, has not been fully utilized.

We have taken glider data from a cruise in the Ligurian Sea (BP'09) and using the SRS technique calculated mean K and then converted to local at each measurement depth interval from ~7 to 95 m at varying and uneven depth increments. The vertical profile is under sampled when compared to the more standard high sampling rates radiometers, like the HyperPRO II. At these low sample densities, one should expect the retrieved K's would be noisy because there is no depth averaging and the near surface (0–10 m) wave focusing and defocusing. The results shown in fig.6 do not show this type of variability and uncertainty and both up- and down-casts were used in the analyses. The depart from a parallel orientation to the sea surface during the down-casts and turning points near the surface and at the bottom of the up- and down-cast does not seem to affect the results. This makes sense in that the SRS is insensitivity to changes in illumination caused by cloud conditions and as shown here the orientation away from the horizontal.

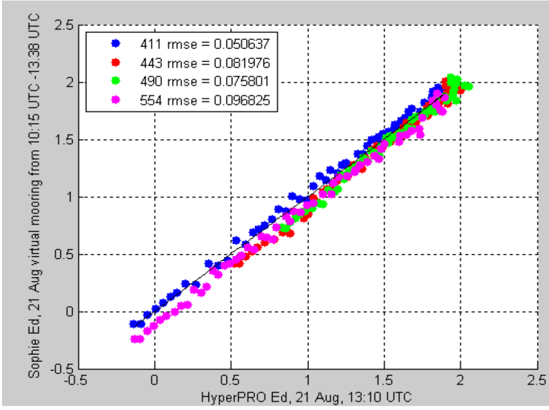

Fig.5. Comparison of downwelling irradiance from a HyperPRO II versus glider data collected on 21 Aug (Sophie glider, left panel).

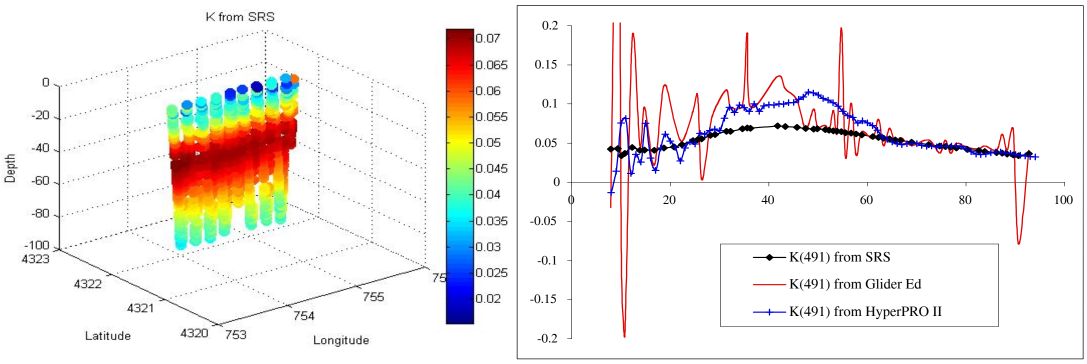

Fig.6. Local *K*(491) calculated from Elettra glider using the SRS technique to include up- and down-casts (left panel). Vertical profiles *K*(491) (right panel) from first down-cast of Elettra glider using SRS (black diamonds), *K*(491) from Elettra glider using only E_d(491) (red line) and *K*(491) from HyperPRO II profile using one meter binned E_d(491).

Conclusions. The downwelling irradiance measured on glider platforms, if extensively calibrated, can be used to retrieve local *K*(490) using the SRS technique. Advantages of this approach is that the incident solar flux does not have to be measured, it works under varying cloud and atmospheric conditions, near surface focusing and defocusing caused by waves does not affect the results, there is no requirement for high density collection of downwelling irradiance and the depth binning (10 to 20 m) of the data to improve retrieval of *Ks* is not required.

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