A profiling optics and water return system for validation and calibration of ocean color imagery

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Abstract: We describe a Profiling Optical and Water Return (POWR) system that has been developed and used extensively at sea. The POWR system is a collection of oceanographic instruments used to measure the inherent optical properties (IOPs) of the upper 100m of the ocean while simultaneously collecting up to eight water samples at various depths for chemical and biological analysis. IOPs are local measurements that are directly related to the properties of the water at the depth sampled; hence it is critical that the water samples be taken at the same time and location as the IOPs. Used during three major experiments, the POWR system has proven valuable for relating IOPs to in-water constituents in support of ocean color remote sensing data product validation, optical model validation, and other interdisciplinary programs.

OCIS codes: (010.4450) Ocean optics.

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1. Introduction

In the coastal ocean, complex interactions between tides, internal waves, coastal jets, upwelling, and outflows from rivers and estuaries can vary the physical, biological, and optical properties on the order of minutes [1]. In addition, phytoplankton blooms are often concentrated in one or more relatively thin layers [e.g., 2, 3], and collecting discrete water samples within these layers is important for determining the overall structure of the water column. Under these circumstances, the need for simultaneous collection of water samples for chemical and biological analysis along with the measured physical and optical properties becomes vital.

To meet this objective, and to improve our understanding of the processes controlling the inherent optical properties (IOPs) in the upper 100m of the coastal ocean, the Naval Research Laboratory (NRL) in Washington, DC, has developed a Profiling Optical and Water Return (POWR) system. The POWR system was designed to collect data to validate and calibrate remotely sensed ocean color data collected by airborne hyperspectral imagers such as the NRL's Ocean PHILLS (Portable Hyperspectral Imager for Low Light Spectroscopy) [4], to relate subsurface optical properties of the water column to remotely-sensed ocean color data, to develop, test, and validate optical models of the coastal ocean, and to provide a platform for testing new in-water instrumentation.

The POWR system is similar in concept to the bio-optical profiling system (BOPS) developed by Smith, et al [5], and the BOPS-II developed by Smith and Menzies [6], in that it incorporates a number of remotely-triggered water sampling bottles into its design. The POWR system differs from the BOPS in that it measures the inherent optical properties (local properties that depend only on the water and other substances that are dissolved or suspended in it), as opposed to the Apparent Optical Properties (AOPs) measured with the BOPS. BOPS is used to measure downwelling irradiance and upwelling radiance and irradiance at a series of depths in the water column. AOPs, such as the downwelling irradiance extinction coefficient Kd are calculated from these measured light fields for some depth interval, and relate to the water column properties over that interval which may or may not be the same as the water properties at the sample depth. The POWR system was deployed during three major field campaigns; the 2001 Hyperspectral Coastal Ocean Dynamics Experiment (HyCODE) [7] at the LEO-15 site off the coast of New Jersey [8], the 2002 Sensor Intercomparison and Merger for Biological and Interdisciplinary Oceanic Studies (SIMBIOS) Coastal Buoyancy Jet experiment (CoJet-7) [9] in the Gulf of Mexico, and the Asian Dust Above Monterey-2003 (ADAM-2003) experiment [10] in Monterey Bay, California. Results from these initial deployments are discussed.

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2. System design

2.1 Design considerations

Paramount to the design of the POWR system were the requirements for a large enough frame to allow for mounting of all desired sensors, and for remotely-triggered water sampling bottles to be integrated directly into the system. Pursuant to this criteria, the POWR system was built around a Seabird Compact Carousel (SBE 32C) frame.

The Compact Carousel was selected to take advantage of the small, sturdy design of the frame, the ability to trigger sampling bottles from the surface, and the ability to replace bottles with vertically mounted instruments. System integration was undertaken by Western Environmental Technology Laboratories, Inc. (WET Labs) in Philomath, Oregon, and was completed in the fall of 2000.

2.2 System description

This multi-instrumented package (Table 1) was designed to measure a wide variety of optical, physical, and biological properties in the upper 100 meters of the water column, while simultaneously collecting water samples at up to eight depths for laboratory measurements of water properties. Data from each sensor is collected and archived onboard the package, then transmitted to the surface via an armored sea cable, where it is stored on a computer disk.

Table 1. Instrumentation used in POWR system

Instrument:	Description of measurement:
WET Labs Histar	Absorption & Attenuation (hyperspectral)
WET Labs ac-9	Absorption & Attenuation at 9 wavelengths
WET Labs ac-9 (filtered)	CDOM Absorption at 9 wavelengths
HOBI Labs Hydroscat-6	Backscattering at 6 wavelengths
WET Labs WetStar	Stimulated Chlorophyll Fluorescence
Seabird CTD-25	Conductivity, Temperature, Depth
Seabird CTD-32	Trigger control for water sample bottles
DataSonics Altimeter	Altitude/Height above sea floor
OceanTest Bottles	Water samples for laboratory analysis
WET Labs SMODAPS	Power distribution and data logging
Sequoia LISST-100 *	Suspended particle size distribution
WET Labs ECO-VSF3 *	Backscattering at 3 angles/3 wavelengths
WET Labs LSS *	Turbidity / suspended solids concentration
WET Labs CDOM WetStar *	CDOM Fluorescence
* Denotes additional instruments used during various experiments	

The package has an operational depth rating of 100 meters and can be used in one of two modes; winch-lowered, where the package is attached to a steel cable and lowered through the water column from a ship mounted boom, or free fall, where custom-designed syntactic foam floats are added to the package to allow it to descend slowly (less than 0.3 meters per second) through the water column (see Fig. 1). In this second and preferred mode, the package is attached to the ship only by a Kevlar reinforced data/power cable, which is hand-fed over the side of the ship during descent and later used to pull the nearly-neutrally buoyant package back up to the surface.

The advantage of the free-fall over winch-lowered mode is that the descent rate of the package is not affected by ship motion or sea-surface conditions. Conversely, free-fall

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becomes a disadvantage when strong currents pull the nearly neutrally buoyant package away from the ship during descent. This results in a diagonal cast and often greatly reduces the maximum depth of the cast due to limited cable length. Retrieval can also be severely hampered by strong currents since the free-fall package must often be pulled back to the ship by hand.

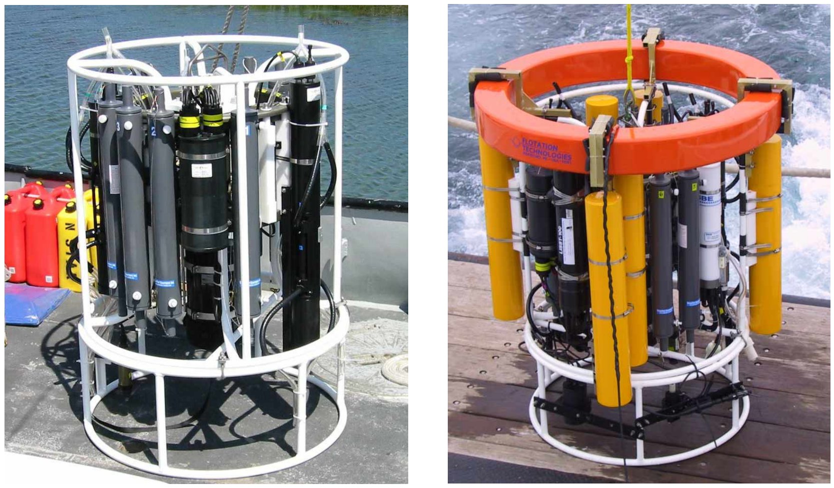

Fig. 1. The POWR system in winch-lowered configuration (left) and free-fall configuration (right) with custom-designed syntactic foam floats (yellow cylinders and orange ring).

3. Calibration and characterization

3.1 Factory calibration

All instruments are sent in for factory calibration on a regular basis, usually at the midpoint between two major cruises. The two ac-9 sensors, Histar, and WetStar Fluorometer, are all calibrated at WET Labs, Inc. in Philomath, Oregon, while the HydroScat-6 is calibrated at HOBI Labs in Issaquah, WA. The remaining instruments, which include the Seabird CTD and the DataSonics bottom ranger do not require regular factory calibrations, unless analysis of the data suggests instrument malfunction, in which case they are sent in immediately.

3.2 Pre-cruise calibration and characterization

Before each deployment, the two ac-9 instruments and the Histar undergo a series of daily calibrations to determine pure water offsets and instrument stability. The day before each calibration, pure water is obtained from a Barnstead Nanopure water purifier and set aside for 24 hours to allow for degassing and debubbling. Then, all windows and tubes of each instrument are cleaned using a combination of Nanopure water and mild soap, rinsed with methanol to remove any remaining soap film, and then gently dried with lint-free lens cleaning paper.

Next, the pure water is vacuum-pumped through each sensor tube individually and the resulting pure-water offset values are recorded. Usually, at least 30 seconds of data are recorded and then averaged to produce the needed offset value for each channel. After all sensors are calibrated in this fashion, the windows and tubes of each instrument are again cleaned and dried following the procedure outlined above.

As a final step before each deployment, air calibrations are performed on each instrument. This involves filling the sensor tubes with nitrogen and recording air values for each

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instrument. These air values help track changes to the sensors due to vibrations or damage during shipping.

The remaining instruments, including the backscatter sensor and CTD, do not usually require pre-cruise calibrations. However, each instrument is thoroughly cleaned, checked for damage, and in-lab data is collected to look for malfunctions.

3.3 Mid-cruise calibration

During the cruise, additional pure water calibrations are performed each evening on both ac-9 instruments and the Histar. The protocol is identical to that described above for pre-cruise calibration. Additionally, if a nitrogen source is available, a single air calibration is performed at the start of the cruise to look for potential shipping damage.

The CTD pressure sensor is also recalibrated during the first cast by resetting the software offset pressure to zero while the instrument is in the water but at the surface. This value is rechecked several times during the cruise.

3.4 Post-cruise calibrations

Following each deployment, air calibrations and another suite of pure water calibrations are again performed on the ac-9 instruments and Histar. The procedures are identical to those listed above for pre-cruise calibrations.

Following the post-cruise calibrations, all calibration data from before, during, and after the cruise are plotted and analyzed to look for trends and sensor drift. If there is no drift present, then final cruise average pure water offset numbers are obtained by averaging all pure water data. If sensor drift is present and believed to be real, then pure water offsets are created from a sliding average to match the time of each cast.

The remaining instruments, including the backscatter sensors and CTD, are checked for shipping damage, and thoroughly cleaned to remove any sea-salt residue and other shipboard contaminants.

4. Data collection

4.1 Deployment

Even though the POWR system can be made neutrally buoyant in the water using syntactic foam or PVC floats, its air weight can exceed 450 lbs when fully instrumented. Therefore, a ship with a boom-winch or A-frame is required to move the package to and from the water.

Just before each cast, Gelman 0.2μm SuporCap Capsule filters are removed from their distilled water storage tub and fitted over the intake tubes of the ac-9 being used for CDOM absorption measurements. We use two filters attached to a Y-connector for each of the two intake tubes. This effectively doubles the surface area of the filters, allowing the pump to pull the sea water through the instrument with less drag, and therefore, increased flow rate to match the flow rate for the unfiltered instruments.

The package is then placed in the water and lowered to a depth of 10 meters (or near bottom in shallower water) where it is held for 3–5 minutes. This allows the motor controller to stabilize in the two ac-9 instruments, the flow tubes to clear themselves of bubbles, and all instruments to equilibrate with the ambient water temperature. The package is then raised back to just below the water surface to begin the cast.

A typical deployment consists of a downward profile followed by an upward profile, both of which are recorded but used differently. The downward cast is the primary source of optical data, due to the location of intake tubes being near the bottom of the package. This reduces water disturbance and allows for a more accurate sampling of the in situ water.

During the down cast, various optical parameters are displayed on laptops onboard the ship and depths of important features such as chlorophyll maximum and thermocline are

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recorded on the station log sheet. Then, during the upward cast, the water sample bottles are triggered at these, and other predefined depths.

Upon returning to the surface, the software is closed and the power to the package is turned off. The package is then re-attached to the winch line (if the line was removed for free-fall mode) and hoisted back to the deck and secured. On some occasions, multiple casts are performed at each station to help distinguish sampling errors from the natural variability of the water column.

4.2 Maintenance

In between each cast, the entire package is rinsed with fresh water and all hoses are flushed for 30 seconds. In addition, the salinity probe of the CTD is flushed and then left filled with distilled water. In addition, the Gelman 0.2μm SuporCap Capsule filters are removed from the package and placed in a covered storage tub filled with distilled water to keep them clean and to reduce air bubbles that would contaminate the data.

If time permits, the windows of the two ac-9s, Histar, and HydroScat are cleaned using a mixture of distilled water and soap, rinsed with distilled water, and then rinsed again using methanol to remove any remaining soap film. If more than an hour is to pass between casts, all windows and flow tubes are dried using lint-free lens cleaning paper.

t the end of the day, this cleaning procedure is repeated, making sure all windows are thoroughly cleaned and dried. The package is then covered with a tarp overnight to reduce the effects of sea-salt spray and other shipboard contaminants on the package.

5. Data processing

5.1 Data extraction

All POWR cast data are initially processed using the current version of the WAP extraction program developed by WET Labs, Inc. This program extracts the archived data using calibration files provided for each instrument, and applies depth and timing corrections to synchronize the data during a profile cast.

5.2 Processing ac-9 and Histar data

Ac-9 and Histar data is then processed in the following steps: First, pure water absorption is subtracted from measured absorption, measured attenuation, and measured gelbstoff absorption data. Next, salinity and temperature scattering corrections are applied to the water-corrected data. The individual data files are then merged by nearest depth and output to text files [11, 12].

Each data file is then sent through a final program where the following processing steps are completed: particulate absorption (a_p) is calculated by subtracting gelbstoff absorption (a_g) from the water-corrected absorption (a_{pg}); particulate attenuation (c_p) is calculated by subtracting gelbstoff absorption (a_g) from the pure water corrected absorption (c_{pg}); apply scattering correction to a_p; then calculate particulate scattering (b_p) using the formula; ($b_p = c_p - a_p$). Note that since the a_g data is recorded by a 9-channel ac-9 instrument, this data was interpolated using a polynomial fit to match the 83 spectral channels of the Histar before being used.

5.3 Processing HydroScat data

After extraction from the archive file, backscattering data from the HydroScat are processed using the HydroSoft software package provided by HOBI Labs, Inc. [13]. Backscattering data are calculated in two stages. The first stage calculates uncorrected backscattering (b_{bu}) for each channel using calibration coefficients, temperature coefficients, instrument temperature, and other variables measured at the factory.

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The second stage involves an adjustment to improve the accuracy of backscattering measurements in highly-attenuating water. Some light that would otherwise be detected as backscattering is lost to attenuation in the water between the instrument and the detection volume, causing backscattering to be underestimated. This error is compensated for this by applying the following correction: ($b_b = \sigma * b_{bu}$), where σ is a correction function called sigma.

Sigma can either be estimated from the HydroScat data or more accurately calculated from ac-9 measurements of absorption and scattering if they are available. By default, we used the later method.

5.4 Data merging and binning

All data files are then remerged and binned to the nearest half-meter using a median filter. Finally, detailed header records are added to each cast file, which include cast time and location information as well as details of the individual processing steps for each instrument. All files are stored in comma-separated ASCII (text) format for easy access.

6. Example results and discussion

IOP values, as measured by the POWR system, are a local measurement that relate to the material located specifically at that depth and sampled with the bottle samples, as opposed to AOP values such as k_d or R_{rs}, which integrate over the water column. The traditional approach for validation of ocean color radiances is to use moored, such as the Marine Optical Buoy (MOBY) [14] or profiling radiometers (e.g. BOPS) to calculate the extinction coefficients and the water leaving radiance. These systems work well in clear waters but have difficulties with instrument shadowing [15] in turbid coastal waters.

IOP measurements use their own light sources and small volumes and work for a much wider range of ocean environments and can be used day or night and under cloudy conditions. In addition, the structures of the water column, including the depth and thickness of any thin layers, often changes rapidly with internal waves [16], exemplifying the need for precise and concurrent water sampling of the specific layers. Under these complex conditions, it is particularly difficult to relate AOPs that are integrated over some depth range to the specific properties of the different layers that may be included in that depth range. Thus, we believe the POWR system measuring IOPs and collecting matched water samples is ideal for optics and remote sensing studies of complex coastal systems.

An example POWR optical profile from the 2001 LEO-15 experiment is seen in Fig. 2. It shows a highly structured water column, typical of that area, with two chlorophyll maximums consisting of a thin layer peaking at 9 meters and a thicker deep layer peaking at 20 meters. The deeper thick layer shows up in the 532nm particulate backscatter ($b_p(532)$) profile, while the shallower thin layer has less backscattering per unit chlorophyll indicating different species or different physiological state of the phytoplankton. Analysis of water samples collected in each layer (not done on this station) would be needed to understand this difference.

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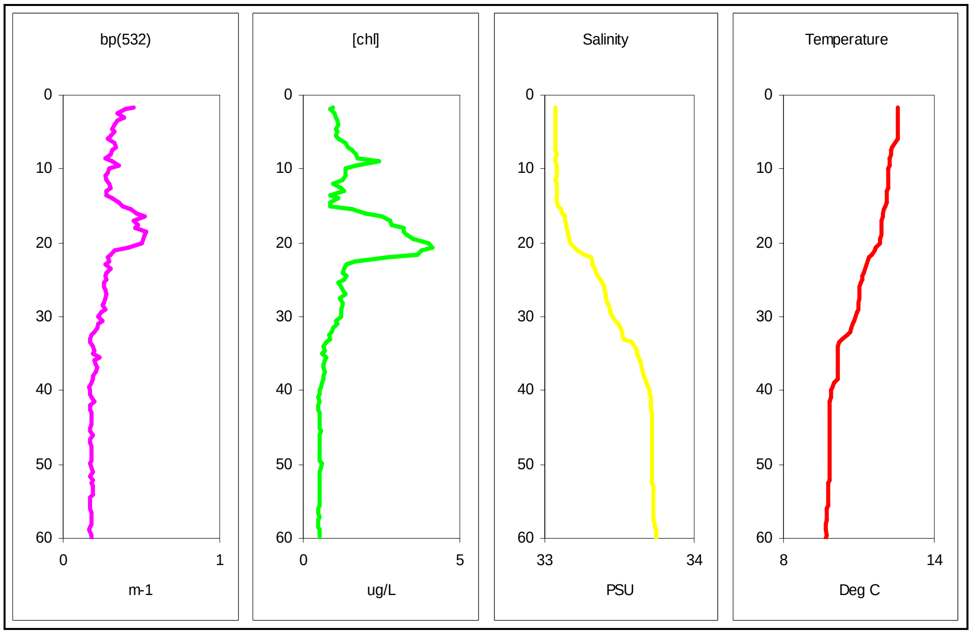

Fig. 2. Example POWR data profile showing a highly structured water column. $b_p(532)$ represents particulate scattering at 532nm, [chl] represents chlorophyll concentration as estimated by measurements of stimulated chlorophyll fluorescence, and salinity and temperature are from the Seabird CTD.

Figure 3 shows the fluorometer profile from Fig. 2 and High Performance Liquid Chromatography (HPLC) measurements from water bottles collected at 3m, 20m, and 47m during this cast. The HPLC data is used to calibrate the fluorescence profile to units of chlorophyll in mg/l. Note that we were able to obtain a water bottle sample at exactly the depth of the 20m chlorophyll maximum, something that would have been difficult using a separate rosette following the optics cast.

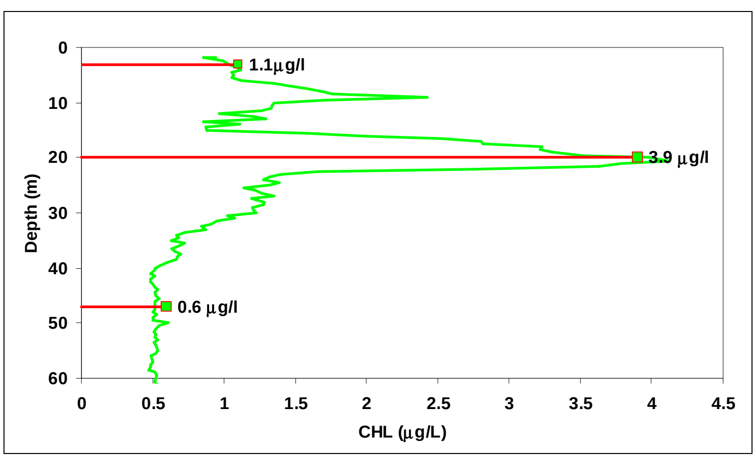

Fig. 3. Example fluorometer profile calibrated using HPLC measurements from water bottles collected at 3m, 20m, and 47m.

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Figure 4 shows two chlorophyll profiles from POWR casts during the ADAM-2003 experiment, with water column structures similar to those in Fig. 2. These casts, taken just 35 minutes apart, show how quickly the water column structure can change in the coastal ocean. If a separate water bottle rosette had been used following the optics cast, it would not have been able to sample the same water column structure, even if it used its own chlorophyll fluorometer to locate the two chlorophyll maximums, since the peaks had changed dramatically in both depth and magnitude during the 35-minute interval.

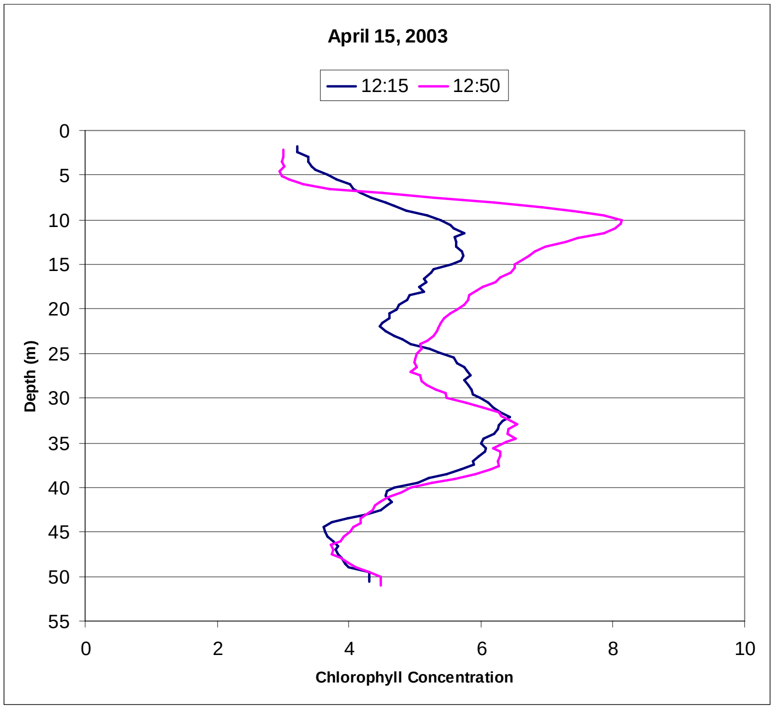

Fig. 4. Example fluorometer profile calibrated using laboratory HPLC measurements from water bottles collected at 3m, 20m, and 47m.

A key goal for the use of POWR was to collect data to validate ocean color products for coastal oceans where using AOP measurements would be difficult. A comparison between POWR data modeled to Remote Sensing Reflectance (R_{rs}) using the Hydrolight [17] radiative transfer program, with above-water measurements using a hand-held Spectrometer made by Analytic Spectral Devices, Inc, and PHILLS hyperspectral imagery collected simultaneously aboard an aircraft flying overhead can be seen in Fig. 5. The modeled data matches the hand-held spectrometer measurements quite well across the spectrum, while the airborne spectrometer data in this case apparently underestimates R_{rs} in wavelengths below 450nm, but generally matches the shape of the other spectra.

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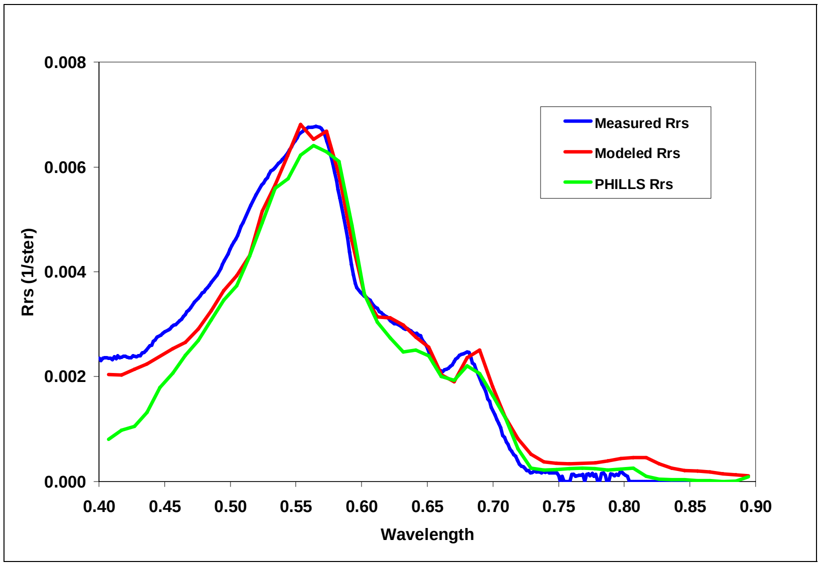

Fig. 5. Example comparison of R_{rs} modeled from POWR data with above-water measurements using a hand-held Spectrometer, and PHILLS hyperspectral imagery.

7. Conclusions

The POWR system was specifically developed to aid in validation and calibration of ocean color imagery collected with airborne hyperspectral imagers over coastal waters and to relate subsurface optical properties of the water column to remotely-sensed ocean color data. During its first 3 years of use, we have demonstrated good agreement between profiled IOP data and above-water radiometric measurements when all individual instruments are working properly and well calibrated. In this way, it has provided a valuable ground-truth for calibrating imagery from the PHILLS hyperspectral sensor, as well as validating atmospheric corrections and in-water product algorithms applied to the imagery.

POWR is a modular system and we recently updated it with the WET Labs ac-s (a hyperspectral absorption and attenuation meter which has replaced the Histar listed above) and a WET Labs ECO-VSF3 (a 3-angle and 3-wavelength volume-scattering meter). The long-term goal is to be able to use a combination of IOP profile data and simultaneously collected water samples to relate the phytoplankton, suspended sediments, CDOM and other properties measured in the water samples to their IOPs and then using HydroLight and other models to relate this data to the above-water parameters as viewed by airborne or satellite-borne hyperspectral imagers.

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