Microradiometers: Hybrid Instrument Building Blocks for Next-Generation Ocean Color Instruments

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***Abstract*—NASA has a current and next-generation requirement to collect high-quality *in-situ* data for the vicarious calibration of ocean color satellite sensors and to validate the algorithms that use the remotely sensed observations. As aquatic remote sensing shifts from the legacy perspective of optically simplistic open oceans toward next-generation observations of myriad optically complex water masses in the coastal zone and polar regions, instrument deployments from small platforms are a necessity. In response to this need, NASA funded the development of a new approach to measuring light: the microradiometer. A microradiometer consists of a photodetector, preamplifier with controllable gain, high resolution (24 bit) analog-to-digital converter (ADC), microprocessor, and an addressable digital port. The microradiometer interface electronics allows sensors that were not traditionally considered "radiometers" to be treated in like fashion by the system electronics, greatly simplifying the addition of other detectors, such as temperature, water pressure, platform angle, or even supply voltage and current. This latter feature inherently leads to the concept of hybrid microradiometers, and because microradiometers simply plug onto the aggregator board stack, unique configurations of hybrid sensing and detecting capabilities are readily imagined.**

Keywords—microradiometer; radiometer; photodetector; apparent optical properties (AOPs); radiance; irradiance; profiles; hybrid instruments

I. MICRORADIOMETERS

In-water legacy systems designed for deep waters with significant mixed layers are not always well suited for properly resolving the optical complexity of shallow waters with one or more thin layers of optically different water types, e.g., freshwater overlying a saltier bottom water. The sampling difficulty is principally a function of overall instrument size, proximity of the deployment platform (a source of perturbations), or the rate of descent for the profiling system. The multidimensional heterogeneity of optically complex waters requires high spatial and temporal resolution, as well as the synthesis of a variety of supporting measurements that need to be made contemporaneously. For example, high-quality coastal data products require more sophisticated atmospheric correction [1] and a greater diversity of water constituent analyses [2].

The design of in situ optical instruments is often a compromise between performance, ruggedness, and consumption parameters (e.g., size, power, bandwidth, and cost). The increased number of spectral bands used by newer remote sensing systems and the wide dynamic range of in situ optical signals places unique challenges on the design of instruments to support next-generation satellite missions. The *microradiometer* (Fig. 1) was developed to meet the need for smaller, faster, and potentially less expensive radiometers, that could be easily scaled to either greater or fewer channels and more easily deployed in optically complex waters, while still being capable of providing high-quality data in the open ocean.

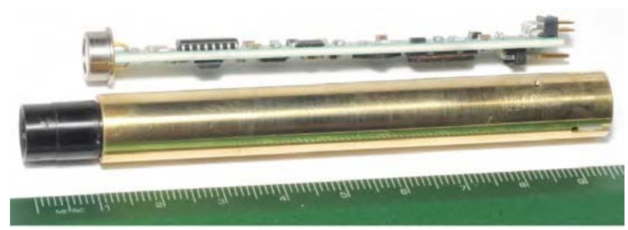

Fig. 1. A side view of a microradiometer showing the two-sided circuit board with photodetector (top), and sleeved with fore-optics (bottom). The centimeter rule is to 9.5 cm.

A microradiometer [3] consists of a photodetector, preamplifier with controllable gain, high-resolution (24 bit) analog-to-digital converter (ADC), microprocessor, and an addressable digital port. It is a fully functional and networkable optical sensor, resident on one small, thin, circuit-board assembly, isolated within a metallic cylinder. With the addition of the front-end optics (diffuser and collector, window, and optical filter stack), the basic form factor resembles a shortened pencil. No multiplexer is required and no internal cabling is needed because each microradiometer board is equipped with an individual ADC, thereby eliminating a source of electronic leakage and improving reliability. Photodiode currents are converted to voltages with a three-gain-stage electrometer amplifier, and the resulting voltage is directly applied to the ADC. Each microradiometer is also equipped with a temperature sensor located proximal to the photodetector. The entire assembly, including the photodetector, is located on a single circuit board measuring 0.9×8.5 cm^2. The metal cylinder provides additional isolation from sources of electromagnetic interference (e.g., radio frequencies).

As a "smart" photodetector module, the microradiometer was envisioned as the heart of a series of highly flexible light-measuring systems. In addition, the microradiometer conceptual approach always included a degree of self-organization that takes advantage of the microprocessor power inherent in each sensor. Clusters of multiple microradiometers can be aggregated together to form multiwavelength radiometers that are easily customized or repurposed as the changing needs for dep-

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loying the instruments requires. This microradiometer architecture is inherently expandable, and up to 200 microradiometers can be used in a multiple-component system with up to 10 data aggregators. Figure 2 shows a functional multichannel radiance sensor, complete with the optical front end, 19 brass-encased individual microradiometers, and an aggregator assembly. A production pressure housing for this radiometer, made from aluminum (not clear acrylic), is 7 cm in outside diameter. The different colors of the 19 apertures correspond to the different wavebands selected for each microradiometer.

Fig. 2. A 19-channel radiance sensor built from microradiometers (the clear acrylic housing is for demonstration purposes only). The microradiometers are encased in brass cylinders and located between the aperture window (with colored filters visible) and the green aggregator and support electronics boards.

MULTIPLE MICRORADIOMETER ARCHITECTURE

Microradiometers are standalone photodetectors, so clustering multiple microradiometers together to build a high-performance instrument system requires additional electronics. The exceptional expandability afforded by the use of microradiometers results from an organizational hierarchy that was designed into the system from the outset. Depending on the complexity of the integration, the basic system architecture for instruments built from microradiometers involves three major classes of electronic devices: a) the microradiometers; b) the aggregator with support electronics modules; and c) a master aggregator module.

Aggregators are used to bundle clusters of microradiometers and ancillary sensors as would typically exist in individual instruments. Aggregators control the data flow to and from microradiometers. They have on-board power control, and may include additional sensors such as tilt sensors, input voltage and current, internal humidity (leak detection), and temperature. For larger sensors with multiple wavebands, a practical issue is the packing efficiency of the cylindrical housings. One of the advantages of the microradiometer architecture is it is relatively easy and low risk to replace or add microradiometers and reconfigure an instrument. Where an aggregator socket is available, a new microradiometer can be added to the initial set simply by plugging one in. The system firmware is designed to be self-organizing, so the change requires no change in software. This flexibility allows a phased approach to expandability and resource allocations. Ancillary devices can also be configured using the microradiometer design to create easily interfaced temperature, conductivity, atmospheric pressure, or other types of ancillary sensors.

When multiple instruments are in operation, a deck box with an embedded master aggregator operates as a high-speed controller. The master aggregator sets the sampling rates and coordinates the polling of all the attached aggregators with their microradiometer assemblies. Further, monitoring for sensor problems and determining their cause(s) is an important function for ensuring successful field deployments and good science. In-water instruments can sometimes fail because of housing leaks. Deployment conditions in the field sometimes require cables that are hundreds of meters long, and experience has shown that field failures are frequently caused by connector or cable problems. In anticipation of these issues, strategies and protocols were implemented in the master aggregator to help ensure reliable field campaigns. These include the following:

- Each microradiometer monitors and reports its supply voltages;
- Each aggregator measures each of the regulated voltages it produces;
- Each aggregator measures its input voltage and current ;
- Each aggregator has built-in pressure and humidity sensors to monitor the atmosphere in the instrument and detect leaks;
- The master aggregator (usually in the deck box) automatically queries each aggregator attached to it, and verifies the voltage levels at the aggregators, and then adjusts the voltage to run the subordinate aggregators at the optimum voltage, thereby eliminating power supply issues caused by increased loads or resistances; and
- The master aggregator can turn off power to either the surface or underwater sensor assemblies if it detects abnormal power consumption or lack of proper response from the remote sensors.

The hierarchical organization in the use of clusters of microradiometers provides an unprecedented ease in interconnecting, modifying, or upgrading the instruments as scientific objectives or financial resources evolve. Unlike legacy instruments, changing, replacing, or repairing a filter, photodetector, or combination thereof for a microradiometer instrument does not require disassembly of the entire electro-optics section. The modularity of the design means it is not a significantly time-consuming and tedious procedure to upgrade an instrument.

This hierarchical flexibility also allows a phased approach to expandability and resource allocations; it also immediately contributes to the concept of using microradiometers to produce hybrid instruments, because the opportunity to construct, reconstruct, or deconstruct what constitutes the instrument is part of the device. Lastly, the added risk of unintended damage to associated components is minimized, as is the time required to test the subassemblies and perform a recalibration. This latter feature naturally leads to the concept of hybrid microradiometers, and because microradiometers simply plug onto the aggregator board stack, unique configurations of hybrid sensing and detecting capabilities are readily imagined.

II. APPLICATIONS

Early in the process of designing instruments using microradiometers, a framework was established to guide the evolution and expansion of AOP instruments into novel deployment opportunities, particularly in light-limited environments. The framework provided upgrade scenarios to match evolutions in resource allocations and science objectives as part of the Scalable Hydro-optical Applications for Light-Limited Oceanography (SHALLO) architecture [4]. The SHALLO architecture recognized that purpose-built instruments have the potential to reduce instrument size, complexity, and costs while retaining the optimal field configuration for optical and ancillary sensors. This philosophy was made more powerful by establishing an outline of modular capabilities for an individual instrument and for instrument systems.

Clusters of microradiometers can be fitted with a variety of fore-optics, forming small, fast, and affordable multiwavelength radiometer systems suitable for a variety of applications spanning above- and in-water observational applications. A number of instrument systems are presented here to illustrate the unique scientific research that can be conducted with instruments built from microradiometer clusters, including the following:

1. The Compact-Optical Profiling System (C-OPS) for collecting vertical profiles of radiance and irradiance in aquatic environments using so-called *hydrobaric* buoyancy control;
2. The Optical Sensors for Planetary Radiant Energy (OSPREy) temperature-controlled hybridspectral radiance and irradiance instruments useful for celestial optical observations, sky and sun photometry, laboratory maintenance of calibration capabilities using transfer radiometry, and the support of the next generation of coupled oceanic and atmospheric remote sensing satellite missions;
3. The Coastal Airborne In-situ Radiometer (C-AIR) instruments for making measurements of water-leaving radiances from airborne vehicles, both manned and unmanned;
4. The Transfluorometer Two-Emission Extension (TF2E), hybrid transfluorometer, which couples light emitting diode (LED) source control with microradiometer detectors to produce a dual waveband fluorometer with ultraviolet (UV) beam transmissometer for use in monitoring organic load changes in urban drinking water storage systems; and
5. The recently funded Ocean Color Underwater Low Light Advanced Radiometer (OCULLAR) hybridnamic pairing of a microradiometer with a photomultiplier tube (PMT) to create a sensor with 16 decades of dynamic range.

Details concerning these five instrument systems are presented below. The presentation also includes examples of how the designs continue to evolve, because of the ease in which microradiometers facilitate the addition of new capabilities that extend the original functionality.

THE COMPACT-OPTICAL PROFILING SYSTEM

In addition to microradiometer sensors, the C-OPS incorporates a number of important advances in field profiling technology [5] beyond the initial architecture envisioned for multiple instrument systems (Fig. 3). These advances include a number of new technologies, each focused on different aspects of the practical problem of resolving the optical complexity of the near-shore water column. Structured around 19 high-speed microradiometer optical sensors, the profiling system includes separate sensors to measure vertical profiles of spectral downward irradiance, and upwelling radiance or irradiance using a variable descent, free-fall backplane. The system is capable of deployments in fresh and marine waters to 125 m depth. A multichamber, hydrobaric buoyancy system provides very slow initial descent rates with ultimate terminal velocities of 5–75 cm s^{-1}, with a typical attitude control to within 2.5° from vertical.

The combination of near-surface loitering, slower and deeper terminal velocities, plus high data rates results in sufficient sample densities to investigate optically diverse, near-surface thin layers, or produce statistically relevant data sets on surface effects as well as the optical properties of the entire water column [6]. Direct benefits of this new sampling capability include lower uncertainties in the data products across the full dynamic range of the sampling problem set, better accuracy in separating the living and nonliving components of seawater, and an improved understanding of the interaction between the ocean and atmosphere.

Because of the 10 decades of dynamic range and unprecedented sampling resolution, above- and in-water instruments built with microradiometers can be used to make high-quality measurements in low-light levels, as originally conceived, Fig. 4, for example, presents in-water measurements of the spectral downward irradiance, $E_d(\lambda)$, where λ is wavelength, made under moonlight. The figure displays a near-infrared wavelength, which is a challenging part of the spectrum under many conditions, but particularly at low-light levels.

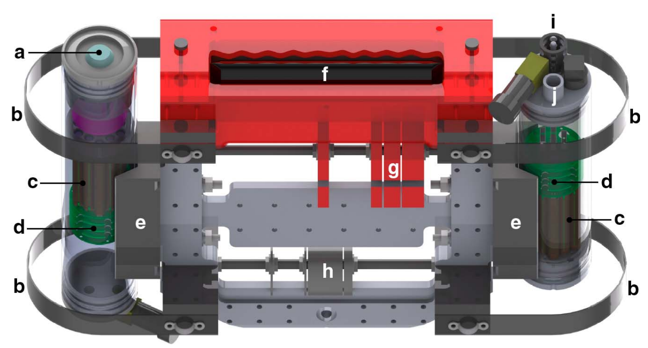

Fig. 3. C-OPS uses 7 cm (OD) sensors and a kite-shaped backplane to accommodate the following: a) cosine collector; b) side bumpers; c) 19 microradiometers cluster; d) new compact aggregator; e) adjustable v-blocks counter pitch biases; f) hydrobaric buoyancy (compressible bladders) allows near- surface loitering; g) adjustable flotation counters roll biases; h) weights (and floats) set terminal velocity and; i) temperature probe and j) pressure transducer.

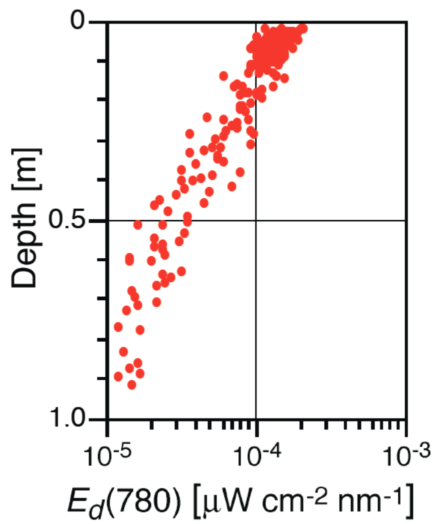

Fig. 4. An $E_d(780)$ vertical profile obtained under the full Moon in Kawaihae, Hawaii.

To further illustrate the capability of the instruments in low-light levels, optical profiles taken with C-OPS in Chesapeake Bay was processed with the NASA Processing of Radiometric Observations of Seawater using Information Technologies (PROSIT) [7] data processor to derive high-quality water-leaving radiance (L_W) and diffuse attenuation coefficient (K_d) data products (Fig. 5). Two types of data were collected: a) measurements from the generalized body of water formed by the open waters of the Chesapeake Bay coves, estuaries, and embayments (green open circles); and b) source waters from an enclosed drainage area of the Blackwater (BW) National Wildlife Refuge (red solid circles), which included sampling in drainage "canals" surrounded by marsh grass beds in waters as shallow as 1.5 m. A comparison of the two water types shows the BW stations are typified by a large range in $K_d(320)$ values relative to $K_d(780)$, with large "headwater" values (BW 55) that fall steadily along a "mixing line" (red) that is distinct from the rest of the Bay until the end of the transect in "open" waters (BW 63). Given that a K_d value of 30m^{-1} represents a vertical scale of approximately 3.3 cm, the data in Fig. 5 also illustrates that observations in shallow coastal waters require sampling systems with unprecedented vertical resolution. C-OPS uses compressible bladders and tunable ballast to control the terminal velocity of the instrument to as low as 5 cm s-1. When this capability is combined with a high data rate of 12 Hz, the vertical resolution in near-surface waters is as small as 1 mm.

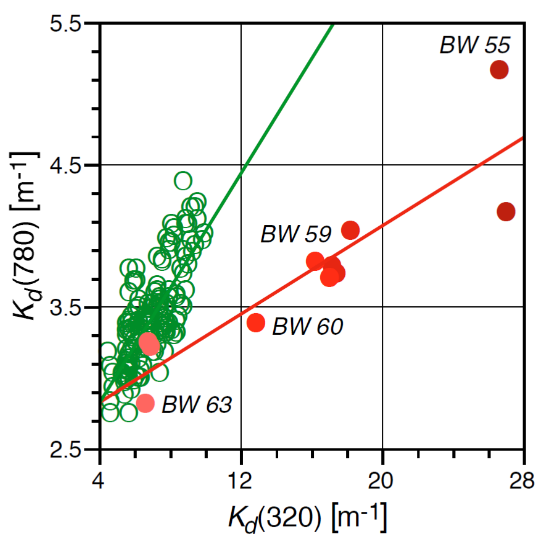

Fig. 5. C-OPS data processed with the NASA PROSIT data processor to return $K_d(320)$ and $K_d(780)$ from two distinct types of water masses: a) Chesapeake Bay coves, estuaries, and embayments (green open circles); and b) source waters from an enclosed drainage area of the Blackwater (BW) National Wildlife Refuge (red solid circles) BW numbers identify the original sampling stations.

The microradiometer interface allows sensors that are not traditionally considered "radiometers" to be treated in like fashion by the system, greatly simplifying the addition of other detectors, such as temperature, water pressure, platform angle, or even supply voltage and current. Most recently, for example, C-OPS was fitted with dual digital thrusters so the instruments can be maneuvered vertically and horizontally in the water column, like a remotely operated vehicle (ROV). Called Compact-Propulsion Option for Profiling Systems (C-PrOPS), the control framework is integrated with the established microradiometer protocols to share a single cable for power, command and control, and telemetry (Fig. 6). C-PrOPS is particularly suitable for deployments in areas unavailable to surface vessels, such as marshes and streams, for work from docks or jetties, and to avoid the turbulence and shading perturbations associated with the deployment platform (e.g., a ship).

The C-PROPS system was field commissioned in June 2013 in concert with another microradiometer extension: the Compact Conductivity Accessory for Profiling Systems (C-CAPS). C-CAPS adds a conductivity and temperature (CT) probe to the optical backplane. There are water masses wherein temperature alone is an inadequate indicator of homogeneity, such as in the Arctic or in estuaries, wherein a thin layer of freshwater overlays more dense oceanic water. The CT probe

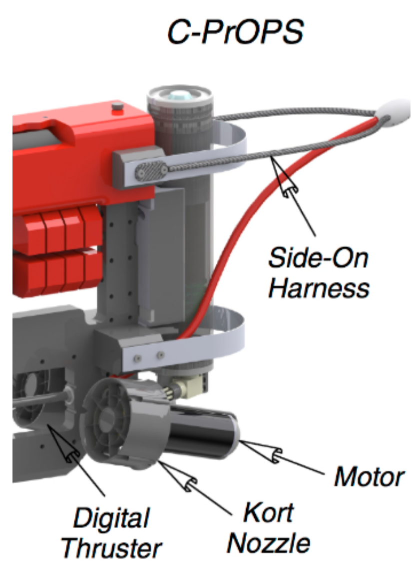

Fig. 6. The Compact-Propulsion Option for Profiling Systems (C-PrOPS) adds digital thrusters to the C-OPS backplane so the instruments can be maneuvered vertically and horizontally.

is a state-of-the-art inductive unit manufactured by Niel Brown Ocean Sensors, Inc. (Falmouth, Massachusetts) and has the highest sampling rate and accuracy in the smallest form factor on the market today.

Optical Sensors for Planetary Radiant Energy

An early exploitation of microradiometers was the Optical Sensors for Planetary Radiant Energy (OSPREy) activity [8] which used the new Enhanced Performance Instrument Class (EPIC) as a foundation for the design (Fig. 7). An EPIC instrument is a hybridspectral device combining measurements of spectral irradiance and radiance from an 18- and 19-cluster (respectively) of microradiometers with a commercially available hyperspectral spectrograph plus a military-grade pointing system. Over common parts of the spectrum, fixed-wavelength microradiometers and the spectrograph can be continuously intracompared to maintain stability and accuracy of the system. Radiance sensors have a nine-position filter-wheel assembly in line with the spectrograph fiber optics to permit hyperspectral polarimetric measurements (three polarized filters), direct-Sun viewing (neutral density filters), stray-light correction (395 nm cut-on filter), and dark current measurements (opaque disk). Radiance sensors also have an integrated camera for locating the Sun and Moon (in lieu of a quadrant detector).

Fig. 7. Synchronous measurements of shrouded (foreground) and unshrouded (background) sky radiance were made at Mauna Loa Observatory (MLO). Radiance instruments are mounted on a military-grade, commercial-off-the-shelf (COTS) tracking system.

Hybridspectral (hyperspectral and fixed-wavelength) observations of solar and lunar irradiances reveal that the spectrograph information may be combined with the microradiometer measurements to return the enhanced spectral information over a very wide dynamic range of fluxes, revealing useful atmospheric features (absorption lines). The consistency in the data suggest good intercalibration and that the Sun and the Moon can be used to monitor sensor performance during clear-sky conditions. Lastly, the data from large zenith angles suggest that sensor calibration from Langley plots, including using the Moon, are feasible.

All OSPREy sensors include thermal stability control to increase filter and detector stability and reduce drift. The field instrument suite includes shadowband accessories to the solar irradiance radiometers, which are combined with radiance observations of the Sun, Moon, sea, and sky across a wide spectral range—the UV, through the visible (VIS) and into the short-wave infrared (SWIR); 305–1,640nm is the full spectral range for radiance, as well as irradiance because of a new cosine collector design [9]. Further, when a single instrument is used to measure the Sun, sky, and sea, the measurements are inherently intercalibrated, which aids to reduce uncertainty budgets for the measurement.

Coastal Airborne In situ Radiometer

C-AIR is an airborne radiometer package which was flown for the first time on the NASA Coastal and Ocean Airborne Science Testbed (COAST) mission over Monterey Bay in 2011. Patterned after the OSPREy above-water microradiometer set, C-AIR consists of three 19-channel microradiometer instruments oriented to simultaneously measure the following: a) sky radiance (L_i), and b) total radiance (L_t) from the surface of the water, and c) global solar irradiance (E_s). The E_s and L_i radiometers are mounted within a nacelle on top of the aircraft and the L_i radiometer is mounted 40 degrees off zenith (Fig. 8). The L_t radiometer is mounted at 40 degrees off nadir. The spectral range of each 19-channel radiometer bundle is 320-780 nm with 10 nm bandwidths to include channels centered around 412, 443, 490, 510, 555, 665, and 683 nm to match satellite bands used for ocean color remote sensing. Application-specific sensors are included such as UV-bands for colored dissolved organic matter (CDOM) or atmospheric correction, bands targeting phycocyanin and phycoerythrin pigments for flights over reservoirs and terrestrial waters (blue-green algae detection), or bands targeting natural fluorescence (for red tide, high sediment load, and primary production applications). The physical field-of-view (FOV) for the radiance instruments is 1.25° half-angle with a 0.7° slope angle.

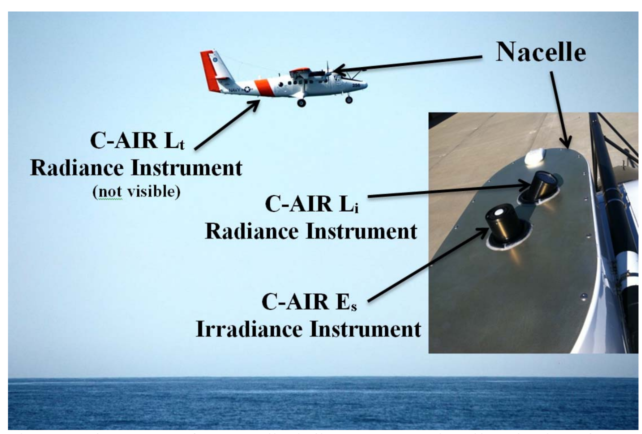

Fig. 8. The Center for Interdisciplinary Remotely-Piloted Aircraft Studies (CIRPAS) UV-18A Twin Otter photographed at 100 feet off the ocean (photo by Juan Torres). The plane is flying over the COAST science team deployed on a coastal research vessel in Monterey Bay. The inset photo shows two of the three C-AIR instruments mounted in a nacelle on the top of the aircraft. The third instrument, which measures radiance, is mounted in the floor of the aircraft.

TRANSFLUOROMETER TWO-EMISSION EXTENSION

For more than a decade, Biospherical Instruments Inc. teamed with the City of Los Angeles to develop the Remote Electro-Optical Sensor (REOS) early warning system to detect increases in the phytoplankton concentration in drinking water reservoirs [10, 11]. This system reduces both the cost of chemical treatment and the concentration of treatment byproducts in open reservoirs. Leveraging the flexibility inherent in the microradiometer design has extended the utility of REOS systems to include a novel inherent optical property (IOP) hybrid instrument, the TF2E is based on modified microradiometer technology (Fig. 9).

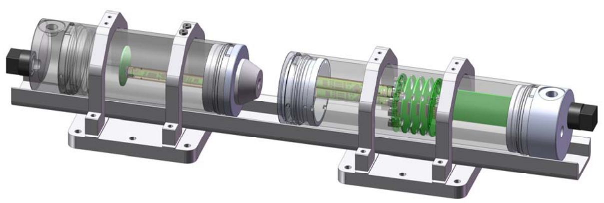

Fig. 9. The prototype AOP and IOP hybrid Transfluorometer (TF2E) leverages microradiometer-controlled LEDs that were developed for linearity testing to produce a dual waveband fluorometer with a beam transmissometer at 289 nm. The fluorometer excitation waveband is 285 nm with emission bands at 350 nm and 555 nm. The system is depicted with a 3 cm path length. The fluorometer FOV is appropriately refraction-corrected for distances that the light rays travel in air, filters, windows, and water.

The TF2E consists of a multichannel fluorometer (285 nm excitation with 350 and 555 nm emission) integrated with a 285 nm single-waveband beam transmissometer for use in drinking water storage tanks. The TF2E incorporates all the necessary microprocessor, digital-to-analog converter, constant-current amplifier, and voltage boost/conversion circuitry needed to power a small LED in a form factor compatible with a microradiometer. The resulting geometry determines the dual fluorometer, transmissometer, and radiometer operation modes. The transmissometer source is an LED at 285 nm with exit optics to produce a relatively narrow beam output, coupled to a beam splitter and mirror reflecting back to a reference microradiometer at 289 nm. A resistance temperature device (RTD) is located near the LED to monitor temperature drift. The transmissometer detector element contains a 289 nm microradiometer, along with a 285 nm fluorescence excitation and biofouling mitigation LED with a flat window for wide FOV output. Microradiometer channels at 340 nm and 555 nm monitor fluorescence. An additional RTD is located in the optics block to monitor temperature drift. Pathlength gauges are available to set the system at 1, 2, 3, 4, and 5 cm gaps.

OCEAN COLOR UNDERWATER LOW LIGHT ADVANCED RADIOMETER

The concept of "paired" measurement types is the basis for the recently funded OCULLAR activity, wherein a ruggedized PMT is paired with a silicon photodetector (SiP) microradiometer. The SiP extends the operating range of the PMT to higher flux levels, and, where there is overlap with the PMT, a calibration path for sources that exceed the saturation levels of the PMT is provided. It is anticipated that the combined PMT-SiP responsivity will provide approximately 16 decades of

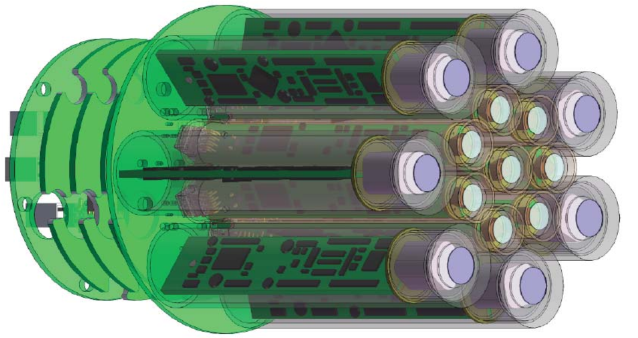

Fig. 10. A concept schematic of an OCULLAR hybridnamic sensor with a cluster of eight smaller microradiometers in the interior, seven of which are paired to the slightly larger PMTs on the exterior circle. The small round left-most boards are the so-called aggregators that allow the cluster of paired PMT and microradiometers sensors to be controlled as a solitary device.

linear calibration. To prevent overexposure that would alter PMT sensitivity or permanently damage it, the microradiometer serves as a monitor to ensure the PMT is only exposed to nominal flux levels. In the simplest description of this pairing, the "smart" microradiometer is being used to "protect" the PMT.

Fig. 10 shows a conceptualization of an OCULLAR hybridnamic instrument with a cluster of eight smaller microradiometers in the interior, seven of which are paired to the slightly larger PMTs on the exterior annulus. The small round left-most boards are the so-called aggregator electronics that allow the cluster of paired PMT and SiP sensors to be controlled as a solitary device.

The eighth microradiometer is not an orphan, because ruggedized PMTs are not available for all desirable wavelengths. For the initial application of building a compact in-water profiler using so-called *hybridnamic* instruments, the eighth microradiometer will provide a near-infrared measurement wavelength. The hybridnamic approach used in OCULLAR is well suited to support the shallow-water, near-shore, and precision sampling objectives driving next-generation missions, which require an unprecedented understanding of the dynamics of coastal ecosystems, river plumes, and tidal fronts; tracking oil spills and other hazardous materials; as well as optical monitoring in regions of special biological significance such as ice edges, marshes, and estuaries [12, 13, 14, 15].

III. SUMMARY

The time span from C-OPS (2005) to OCULLAR (2013) oversaw a significant evolution in field instrument capability, largely by exploiting the fact that microradiometers are programmable and networkable, resulting in "smart" and self-organizing photodetectors. Microradiometers are capable of interacting to extend instrument capabilities beyond the original photodetector-only design. This flexibility permits a greater diversity of interactions at the sensor level, and facilitates the collection of more diverse types of observations from both passive and active devices in the same instrument housing. Looking ahead, it is not difficult to imagine a hybrid instrument melding AOP and IOP detection technologies such as scattering and fluorescence. The use of shared detectors and microradiometer-controlled LEDs provides that the measurements are synchronous and optically intercalibrated.

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