# Hybrid Atmosphere, Land, and Ocean (HALO) Sensors for Next-Generation NASA Missions


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## HALO Introduction and Overview

The NRC Decadal Survey (NDS) advocates that the "validation of geophysical products inferred from satellite remote sensing is essential." Furthermore, for the development of climate data records, "validation should be an almost continuous component, providing an independent check on the performance of space-based sensors and processing algorithms." The Climate-Centric Architecture (CCA) report notes that "it is incumbent on the providers of satellite data to take particular care that the consistency between related data sets is well documented." For the inevitable need to create comprehensive data products from diverse organizations and instruments, the NASA CCA requires "calibration and validation throughout all stages of the process."

This poster presents recent advancements in the development of a class of above and in-water instruments for multidisciplinary research and satellite calibration and validation called, Hybrid Atmospheric, Land, and Ocean (HALO) sensors. The initial accomplishments include results from the Optical Sensors for Planetary Radiant Energy (OSPREy) project, a state-of-the-art, above-water, hybrid radiometer system for the calibration and validation of current and next-generation satellite missions. An OSPREy system, consisting of radiance radiometers mounted on computer-controlled pointing systems and irradiance radiometers equipped with shadowbands, combines the new microradiometer technology from Biospherical Instruments Inc. (San Diego, CA) with high-quality spectrographs to produce a suite of diverse instrument configurations sharing a common architecture. Located on a variety of platforms (e.g., off-shore platforms, coastal vessels, or terrestrial towers), OSPREy instruments provide high-quality measurements of the direct Sun, land or sea surfaces, the sky, and the Moon over the spectral range of 305–1,640 nm.

OSPREy measurements are traceable to the radiometric scale maintained by the facility for Spectral Irradiance and Radiance Responsivity Calibrations using Uniform Sources (SIRCUS) operated by the National Institute of Standards and Technology (NIST). Furthermore, OSPREy measurements have a documented uncertainty satisfying the accuracy requirements for the vicarious calibration of satellites, making it the only commercially available satellite calibration and validation system. The NIST/SIRCUS radiometric scale is transferred to OSPREy field instruments using OSPREy Transfer Radiometers (OXR).

Complementing above-water OSPREy measurements, commercial, off-the-shelf (COTS) microradiometer technology is available for in-water determinations of apparent optical properties (AOP) using the Compact Optical Profiling System (C-OPS; Morrow et al. 2010). As part of HALO, and complementing above-water OSPREy measurements, microradiometer and spectrograph technologies are being integrated to produce a new, multipurpose hybrid in-water system, the Compact-Profiling Hybrid Instruments for Radiometry and Ecology (C-PHIRE).

### Deployment Options

OSPREy was originally developed in support of ocean color measurements. For this application, deployment at the end of a long pier or an off-shore platform is envisioned (Fig. 1).

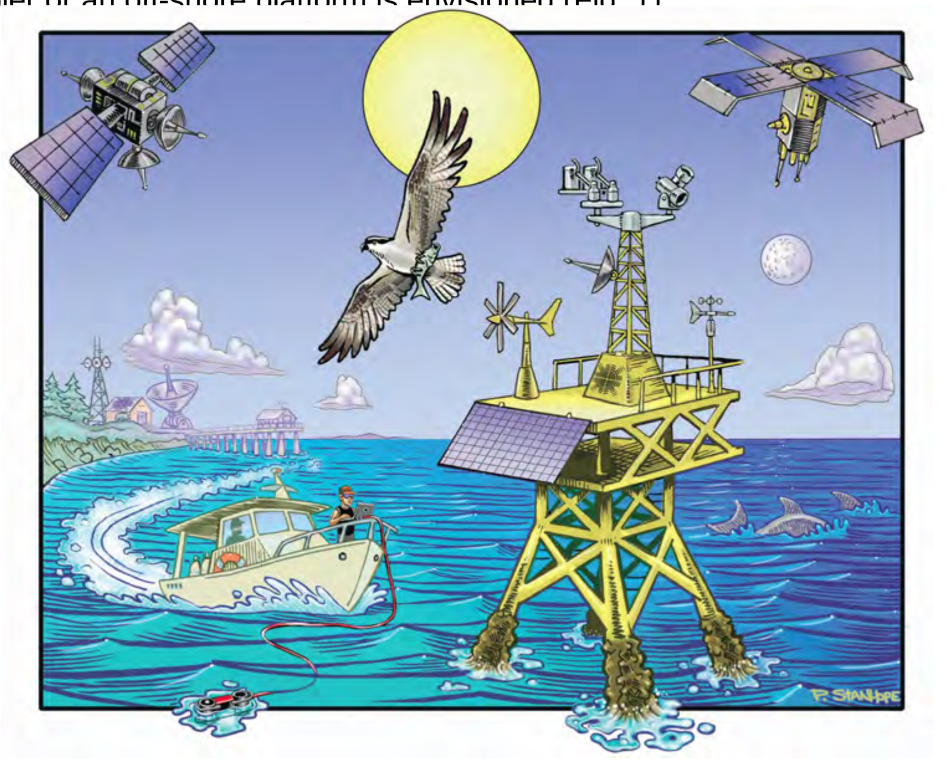

Figure 1. Deployment example for an OSPREy system in support of ocean color research: an *OSPREy Operational System* (Fig. 7.4), consisting of two EPIC dyads, is mounted on top of an offshore tower. Also shown are solar panels and a wind generator for providing power; the ocean color satellite to be validated; a telecommunications satellite for data telemetry; a shore-based calibration and logistical support facility; and regular quality control visits using a small boat. The latter includes the sampling of in-water optical profiles with the C-PHIRE System shown in Fig. 8.

For the validation of satellite data products, OSPREy sensors can be mounted on sturdy tripods, vehicles, or tall masts. Other HALO sensors can also be integrated in aircraft (e.g., a zenith-viewing irradiance sensor paired with an off-nadir-viewing radiance sensor). By removing temperature stabilization and the spectrograph from the sensor, form factor and power consumption can be reduced allowing the system to be installed in an unmanned aerial vehicle (UAV). A unique benefit of this HALO approach is the reduced uncertainty from deploying the ***same*** technology both above and in-water.

## OSPREy Systems

OSPREy field radiometers are part of BSI's line of Enhanced Performance Class (EPIC) instruments, which are temperature-stabilized hybrid sensors composed of fixed-wavelength microradiometers and a hyperspectral spectrograph. Figure 3 shows a diagram of an EPIC radiance radiometer. OSPREy systems consist of one or several irradiance and radiance radiometers. Instruments for measuring irradiance use a cosine collector and can be equipped with a shadowband (Fig. 4) to measure both the global and diffuse solar irradiance. The instruments can also be mounted inverted to measure surface reflectance. The radiance radiometers are mounted on a pointing device (Fig. 5) to measure either the Sun, sky, surface, ocean, or Moon. When pointing at the Sun, the radiance instrument becomes a state-of-the-art sun photometer. Each instrument is controlled by a ruggedized computer.

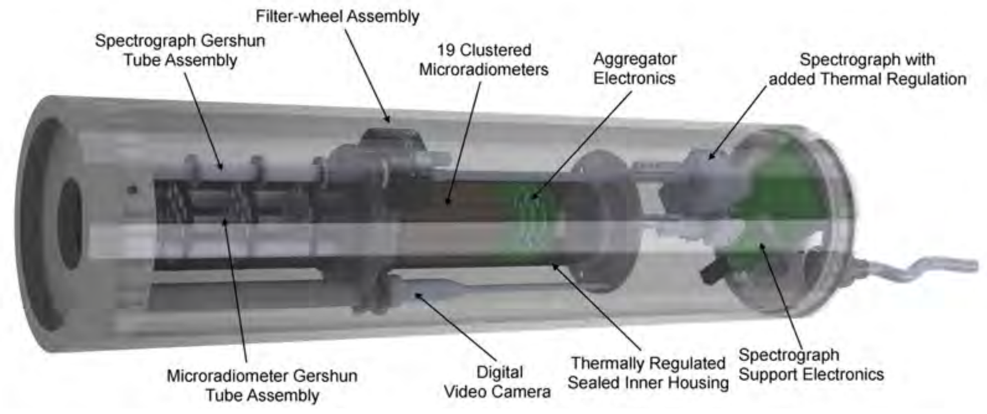


Figure 3. An EPIC radiance radiometer used for OSPREy. The instrument is equipped with two Gershun tube assemblies, one for the microradiometer cluster and one for the spectrograph, both with a field of view of 2.5°. Microradiometer channels cover the wavelength range of 340–1,640 nm. A nine-position filter-wheel assembly is mounted in line with the radiance spectrograph to provide hyperspectral polarimetric measurements (three polarized filters), direct-Sun viewing (two neutral density filters), stray-light correction (395 nm cut-on filter), dark current measurements (solid disk), and a home position. A video camera is used for locating the Sun (in lieu of a quadrant detector) and verifying the condition of all targets (e.g., cloud-free solar disk, cloud presence in sky data, and sea surface debris or foam detection). Using these data, small alignment errors (e.g., leveling) of the sun-tracking mode can be easily quantified and corrected.

### Integrated Spectrograph

EPIC sensors are equipped with a spectrograph featuring a rugged, monolithic design where all optical components are firmly cemented to a body of UBK7 glass, resulting in high wavelength stability and reliability. Thus, EPIC systems combine the superiorities of microradiometer technology (e.g., large dynamic range, excellent temporal stability, low stray light, and high scan speed of up to 20 Hz) with the spectral resolution of a spectrograph. Microradiometers and the spectrograph are temperature regulated to better than ±0.1°C.

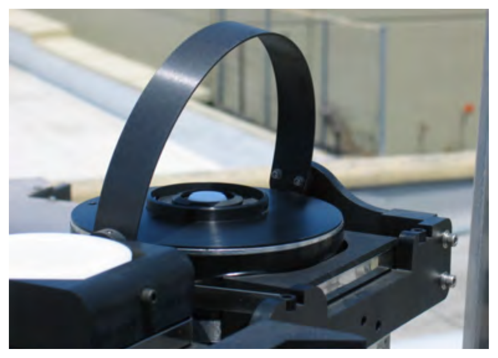

Figure 4. Shadowband assembly mounted on an irradiance radiometer. The band can be programmed to track the Sun or sweep across the sky.

Figure 5. OSPREy radiance radiometer mounted on the pointing device and tracking the Sun.

## OSPREy Technology Advantages

OSPREy systems are robotic and their observation sequence can be optimized for the research application in question. Systems consisting of several instruments (e.g., Fig. 6.2–6.5) can be used in synchronous and asynchronous modes. The only other commercial instrument with similar capabilities as the OSPREy radiance sensor is the CE-318 from CIMEL Electronique (Paris, France), which is used in NASA's Aerosol Robotic Network (AERONET) and the SeaWiFS Photometer Revision for Incident Surface Measurements (SeaPRISM) system for measuring water-leaving radiance. The OSPREy technology has several advantages compared to the CE-318:

- OSPREy sensors measure all wavelengths simultaneously with sampling rates of up to 20 Hz, which allows for filtering of surface wave effects in ocean-viewing applications.
- The radiance distribution of sky light or the bidirectional reflectance distribution function (BRDF) of Earth's surface can be measured within short time periods because of the high angular velocity of the tracker of up to 50° per second.
- OSPREy systems permit seamless integration of an irradiance sensor (i.e., a solar reference).
- With the use of InGaAs detectors for the SWIR, filter channels of EPIC radiometers can span a wavelength range of 305–1,640 nm (the CE-318 uses a single silicon detector, which is radiation insensitive beyond 1,100 nm).
- The spectrograph internal to EPIC radiometers offers a more accurate mechanism to interpolate between the measurements of the filter wavelengths than is possible with SeaPRISM.
- The spectrograph component of EPIC radiometers has three polarizers at 0, 45, and 90° for sky and sea Stokes vector determinations. (SeaPRISM can have one polarization wavelength, but that option reduces the wavelengths to six.)

## OSPREy Configurations

OSPREy systems are modular and can be easily reconfigured to meet the requirements for the validation application in question (Fig. 6.) A single radiance sensor (Fig. 6.1) presents a state-of-the-art sun photometer and can also serve as a viable replacement for the only existing autonomous above-water ocean color validation system, called the SeaWiFS Photometer Revision for Incident Surface Measurements (SeaPRISM). Adding an irradiance sensor with shadowband accessory (Fig. 5) provides redundancy and simultaneous sampling, which yields enhanced quality assurance (QA) and data products (Fig. 6.2). Optimized cosine response from two irradiance sensors (Fig. 6.3) provides a triad with potentially the lowest uncertainties for irradiance and the first opportunity for synchronous and asynchronous sampling, which improves QA and reduces uncertainties. Two dyads (Fig. 6.4) provide significant redundancy, which minimizes risk, and the synchronous and asynchronous sampling enhances data products and QA. Two triads provides optimized data products across all wavelengths and, thus, the lowest uncertainties (Fig. 6.5).

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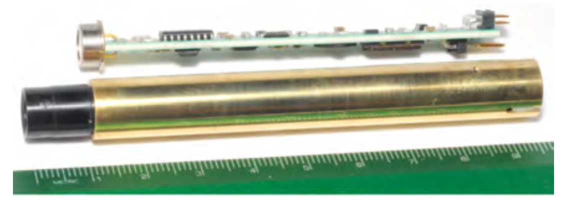
| 1 | ***Starter System*** • 8–19 Channels • One radiance sensor (SeaPRISM analog) • Manual or fixed options | ***Measurements, Data Products, and Mission Advantages*** • EPIC sensors expandable to 19 wavebands from 305–1,670 nm • Temperature stabilized, hyperspectral, video camera, and seven-position filter-wheel assembly (permits polarimetry) options • Direct solar, sky, sea, and lunar radiance measurements |
| 2 | ***Minimum System*** • Radiance and irradiance • Some redundancy (both measure the Sun) • Shadowband optional | ***All of the Above, and in Addition:*** • Global irradiance plus diffuse component (using shadowband) • Direct-to-global irradiance ratio (used for cosine-error correction) • Improved data products and adds cloud optical depth • Enhanced quality assurance from two solar measurements |
| 3 | ***Spectral System*** • Two irradiance sensors with shadowbands • One radiance sensor • High accuracy | ***All of the Above, and in Addition:*** • Two optimized cosine collectors for high irradiance accuracy (305–700 nm and 600–1,670 nm) • Up to 38 channels for irradiance or enhanced redundancy • Synchronous and asynchronous shadowband operation |
| 4 | ***Operational System*** • Up to 38 channels of radiance and irradiance • Synchronous and asynchronous data products | ***All of Systems 1 and 2, and in Addition:*** • Redundancy minimizes risk (data loss from sensor malfunction) • Enhanced data products from synchronous sampling scenarios • Detection of thin cirrus clouds from asynchronous scenarios • Maximum fixed wavelength sampling can be optimized instead |
| 5 | ***Maximum System*** • Two complete triads • Maximum redundancy and spectral coverage • Maximum data quality | ***All of the Above, and in Addition:*** • Maximum risk reduction (full instrument redundancy) • Maximum QA and QC (faulty channels can be quickly identified) • Maximum number and quality of data products • Maximum number of synchronous and asynchronous scenarios |

Figure 6. Configuration examples of EPIC sensors.

## Microradiometers

The technology used to produce the fixed-wavelength component of EPIC sensors is based on microradiometers, which were developed by Biospherical Instruments Inc. with funding from NASA. 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. It is a fully functional, networkable sensor, resident on one small, thin, circuit-board assembly that is sleeved inside a small cylindrical shield (Fig. 7). With the addition of the front-end optics (collector, window, and filter stack to set the center wavelength and bandwidth), the basic form factor resembles a shortened pencil. The microradiometer was developed in response to a need for smaller, faster, and potentially less expensive radiometers, which could be easily scaled to either more or fewer channels and more easily deployed in coastal waters where self-shading effects are frequently significant. EPIC instruments typically feature a cluster of 18 or 19 temperature-stabilized microradiometers covering the wavelength range of 340–1,640 nm (UV to SWIR) at a spectral bandwidth of 10 nm.

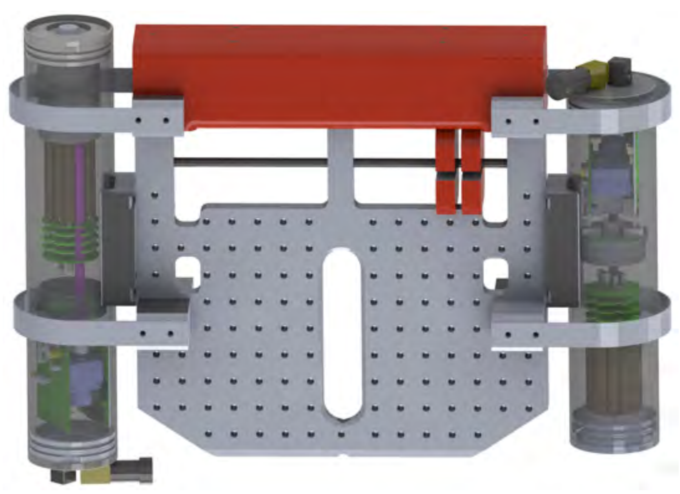
Figure 7. A side view of a microradiometer showing the two-sided circuit board design (top), and a sleeved version with fore-optics attached (bottom). The ruler is marked in centimeters.



**Compact-Profiling Hybrid Instrumentation for Radiometry and Ecology (C-PHIRE) : a Hybrid Instrument for Multidisciplinary Research**

C-PHIRE (Fig. 8) is a COTS spin-off from a NASA instrument development activity to produce hybrid sensors for above-water calibration and validation activities (Hooker *et al.* 2011). The C-PHIRE design uses OSPREy technology housed in a smaller form factor that is watertight, and positioned on a backplane patterned after C-OPS. The result is an hybrid optical system that uses highly accurate microradiometers to continuously verify the stability and accuracy of the embedded spectrographs. The 18 ($L_u$) or 19 ($E_d$) microradiometer wavebands span 320–860 nm and the spectrograph covers 250–785 nm with a bandwidth of 7 nm (256 pixels). C-PHIRE is capable of acquiring near-surface profiles of unprecedented spectral and vertical resolution.

Figure 8. The C-PHIRE instrument with a hybrid irradiance sensor on the left and a hybrid radiance sensor on the right (with temperature and pressure transducers on the upward facing end cap). The top-most red floatation block houses 1–3 compressible air bladders. As the bladders compress, the package descends more quickly. The initial slow descent rate ensures high vertical resolution near the sea surface.



## Data Products

OSPREy systems can produce an unprecedented number of data products that are relevant for validation and research applications of the atmospheric, oceanic, and terrestrial research communities. An OSPREy radiance radiometer mounted on the tracking device is a state-of-the-art robotic sun photometer and can also be used for BRDF measurements of the surface.

**Atmospheric Data Products**
- Total ozone column
- Aerosol optical depth (AOD)
- Aerosol absorption
- AOD for fine and coarse mode aerosols
- Aerosol size and effective radius
- Aerosol phase function
- Almucantar and principal plane scans; sky scans
- Refractive index (both real and imaginary parts)
- Cloud optical thickness
- Precipitable water vapor
- Global and diffuse spectral irradiance
- Radiative forcing induced by aerosols
- Degree of polarization of sky radiation, Stokes vector

**Oceanic Data Products**
- Water-leaving radiance, Chl *a*, turbidity
- Remote Sensing Reflectance
- Suspended or dissolved matter

**Terrestrial Data Products**
- Surface reflectance
- Bidirectional Reflectance Distribution Function (BRDF)
- Vegetation characterization/Leaf Area Index (LAI)
- Snow properties
- Fraction of Photosynthetically Active Radiation used by plants

## Relevance to GEO-CAPE

The marine biosphere is composed of myriad physical, chemical, biological, and ecological processes, all of which are integral parts of planetary biogeochemical cycles (e.g., carbon, nitrogen, phosphorous, silica, iron, etc.). These cycles are coupled to, and influence climate through, feedback processes that are not clearly understood.

The NRC Decadal Survey (NDS) recognized the importance of satellite data for investigating these processes and recommended three missions designed to acquire data regarding the distribution of marine biosphere properties (HyspIRI, GEO-CAPE, and ACE). In describing the recommended ocean color missions, the NDS highlighted the need for continued measurement of ecosystem function, water quality, productivity, biogeochemistry, and onset of algal blooms. These same missions would also provide observations on aerosol properties, gas columns, and air quality. Implicit in the required observations is the need to understand how oceanic and atmospheric systems are changing, in terms of the corresponding distribution and composition of the parameters involved, as well as the regulating processes. This means field campaigns are needed well in advance of the anticipated launches to establish baseline understandings, data product algorithms, plus calibration and validation capabilities.

HALO systems such as OSPREy and C-PHIRE will help develop, calibrate, and validate a suite of oceanic and atmospheric retrieval algorithms that can be directly adapted to current and next-generation missions such as GEO-CAPE. The state-of-the-art technology that has been developed for OSPREy will provide robust data because of the hybrid design (highly accurate fixed wavelength microradiometers verify the calibration of the hyperspectral data) and the attention to reducing uncertainties (e.g., accurate metrology, thermal regulation, and stray light correction).

## References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