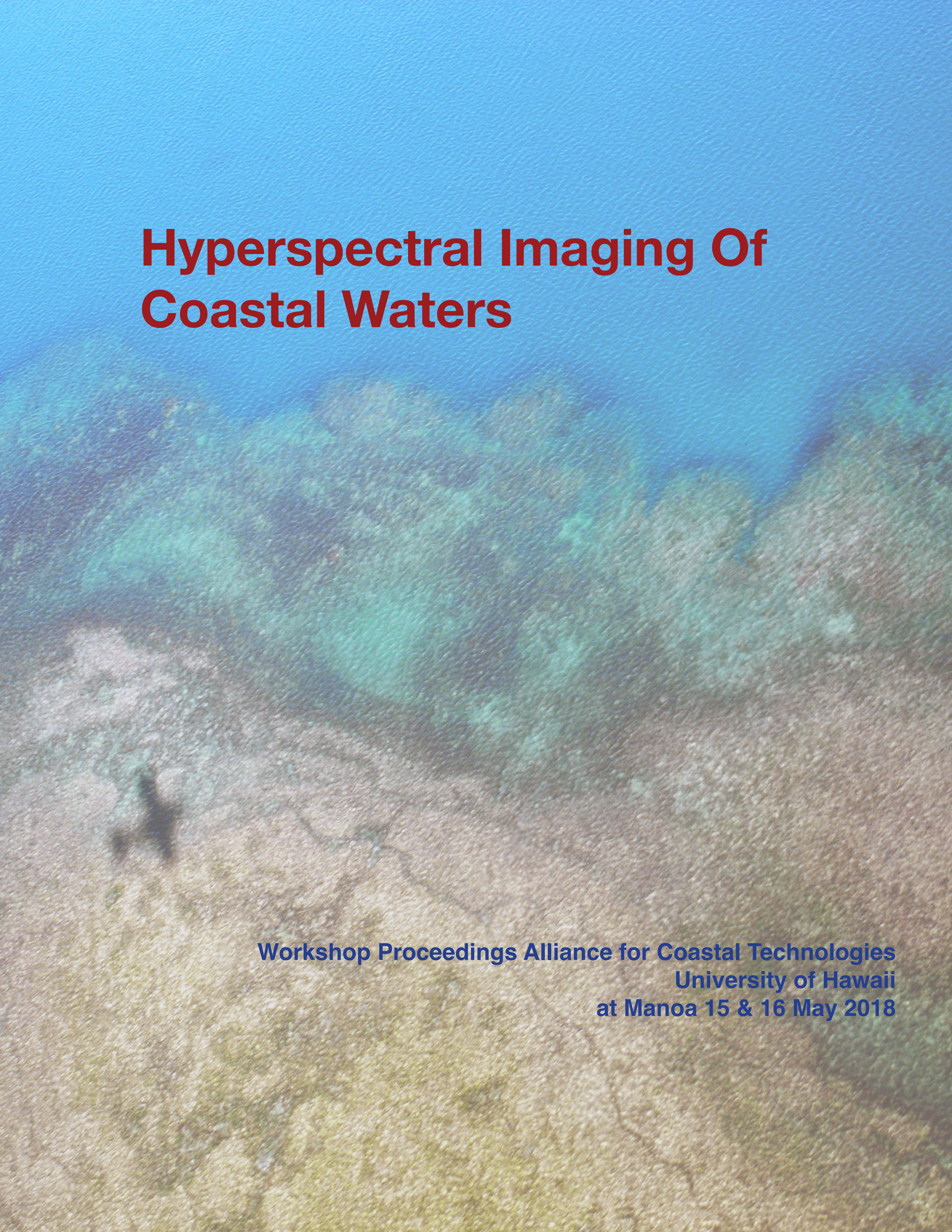

Hyperspectral Imaging Of Coastal Waters

Workshop Proceedings Alliance for Coastal Technologies
University of Hawaii
at Manoa 15 & 16 May 2018

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Workshop Proceedings
Alliance for Coastal Technologies

HYPERSPECTRAL IMAGING OF COASTAL WATERS

University of Hawaii at Manoa
15 & 16 May 2018

This workshop was organized and hosted by the Alliance for Coastal Technologies (ACT) and sponsored by the National Oceanic & Atmospheric Administration (NOAA)/US Integrated Ocean Observing System (IOOS)

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EXECUTIVE SUMMARY

The Alliance for Coastal Technologies (ACT, www.act-us.info) convened a workshop on "Hyperspectral Imaging of Coastal Waters" in Honolulu, Hawaii at the East-West Center on 15 and 16 May 2018. This workshop was organized and hosted by the Alliance for Coastal Technologies (ACT) and sponsored by the National Oceanic and Atmospheric Administration (NOAA)/US Integrated Ocean Observing System (IOOS). The primary objectives of this workshop were to: 1) describe the state of the technology for a variety of coastal environments; including but not limited to coral, kelp, harmful algal blooms, water quality, 2) discuss where advances in technology might occur over the next decade; and 3) determine if it would be appropriate for ACT to undertake a demonstration of technology. The participants were from various sectors including research scientists, technology developers, industry providers and technology users.

The prioritized list of recommendations emerging from this workshop include a list of possible demonstration projects that ACT might undertake. These demonstration include: 1) Processing algorithm round-robin, 2) Mooring calibration/validation of hyperspectral remote sensing, 3) Controlled observations in tanks/mesocosms and 4) Flight comparison with Portable Remote Imaging Spectrometer (PRISM) as standard. Detailed descriptions of these recommendations can be found on pages 18-22.

ALLIANCE FOR COASTAL TECHNOLOGIES

One of the greatest challenges that NOAA faces in incorporating advanced technologies is bridging the Technology Readiness Level gap between developmental and operational instrumentation. Efforts dedicated to maturing observing technologies to operational readiness through rigorous and relevant testing, while simultaneously building user confidence and capacity, continue to be critical. Building on over a decade of experience in facilitating the development and adoption of environmental observing instrumentation, the Alliance for Coastal Technologies (ACT, www.act-us.info), proposes to work in collaboration with U.S. IOOS Program Office and Regional Associations (RAs), IOOS federal and non-federal partners, local and regional resource managers, academic researchers and the private sector to improve operational observation capabilities through the quantification of existing instrument performance, and the introduction of new technologies, and enhanced communications. ACT's mission is to foster the creation of new ideas, new skills, new technologies, new capabilities, and new economic opportunities in support of the sustained national IOOS.

ACT was established by NOAA in 2001 to bring about fundamental changes to environmental technology innovation and research to operations practices. ACT achieves its goal through specific technology transition efforts involving both emerging and commercial technologies with the explicit involvement of resource managers, small and medium-sized firms, world-class marine science institutions, and NOAA and other Federal agencies. ACT's core efforts are:

1) Technology Evaluations for independent verification and validation of technologies,
2) Technology Workshops for capacity- and consensus-building and networking, and
3) Technology Information Clearinghouse including an online Technologies Database.

ACT is the world's leader in the evaluation of commercial and emerging ocean, coastal and freshwater sensing technologies. ACT's Technology Evaluations employ an ISO/IEC 17025:2005 compliant process to generate sensor performance data of known and documented quality through an open, inclusive, and transparent process that is responsive to the *users' operational needs*. Evaluations focus on classes of instruments to demonstrate capabilities/potential of emerging technologies, provide unequivocal verification of performance specifications for commercial technologies, and/or provide validation of instrument operational qualifications that meet users or observing system requirements. Laboratory and field testing is carried out under reproducible, well-understood conditions, which allows manufacturers to assess and improve components, configurations, and designs as necessary. Since 2004, ACT has evaluated nearly 90 sensors from 32 international companies. Results of ACT Technology Evaluations also have provided important insights to users on how to interpret data provided by in situ instrumentation and thus how to appropriately quantify various environmental parameters. The ACT Evaluations provide independent assurance that basic science understanding, forecasting, and management decisions are based on accurate, precise, and comparable observing data, while minimizing the risk of artifacts and problems associated with young technology.

ACT Technology Workshops have addressed the capabilities of existing operational technologies (e.g., dissolved oxygen and salinity) and needs for new technological solutions to address specific global environmental issues (e.g., nutrients pollution and ocean acidification). Encouragement of the private sector as participants not only provides users with opportunities to better understand technology options, but also helps technology providers to better understand customers' needs.

The ACT Information Clearinghouse includes all Technology Evaluation and Workshop reports (as downloadable PDFs) and a stakeholder driven database that compiles and inventories information on observing technologies. The Technology Database now connects users with over 400 companies and nearly 4,000 commercial instruments, which increases awareness of technology customers, users, regulators and policymakers of available technology options.

WORKSHOP GOALS AND QUESTIONS

The overarching goals of the ACT workshop on "Hyperspectral[1] Imaging of Coastal Waters" were to examine present hyperspectral imaging technologies in coastal environments, to explore future requirements for hyperspectral imaging, and to determine if it would be appropriate for ACT to undertake a demonstration of these technologies and data processing methods.

Specific questions that were discussed during the two-day workshop included:

1) Why use hyperspectral imaging in coastal waters?
    a. For what fundamental question(s) is the technology (potentially) useful or necessary?
    b. What observations can be made using this technology that can't be made using other methods?
    c. Which methods are complementary to hyperspectral imaging? How?
    d. What does the non-specialist community want to measure?

2) What is the current status of the technology? (i.e., *current* science requirements, observables, observation requirements)
    a. What geophysical parameters are currently retrieved?
    b. How accurately are they retrieved?
    c. What limits retrievals?
    d. What successes have there been?
    e. What lessons have we learned?
    f. What is the typical workflow for hyperspectral image processing? What is the status of open source tools for image processing?
    g. What types of platforms, e.g., unmanned aerial vehicle (UAV), manned aircraft, cubesats and SmallSats (https://www.nasa.gov/content/what-are-smallsats-and-cubesats), low Earth orbit (LEO) satellite) currently support hyperspectral imagers?
    h. What are the observational/instrumental requirements for a particular science need?
    i. What is the status of calibration/validation activities?

3) Where do we see the field in 10+ years? (i.e., *future* goals, observables, requirements)
    a. What coastal environmental properties might/should be measured?

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[1] Continuous spectra from the UV to the NIR at 10 nm spectral bandwidth or better.

b. What accuracy is required?
c. How do we get there?
d. How should automation of image processing be prioritized?
e. How should the difficulties in atmospherically correcting hyperspectral imagery be mitigated?
f. How should calibration/validation activities evolve?
g. What types of platforms should be prioritized (e.g. geostationary satellite, LEO satellites, airborne, UAV, water/land surface instruments)?

4) What would a demonstration project look like?
   a. Where?
   b. Why the given location(s)?
   c. What geophysical parameters?
   d. What validation?
   e. Which instrument(s)?
   f. Geometric and radiometric calibrations?
   g. Flight logistics: planning, airport(s), FBO(s), aircraft, clearance, instrument install, flight engineer(s), pilots, instrument uninstall?
   h. Image data processing and analysis (from digital numbers to data products)?

ORGANIZATION OF THE WORKSHOP

This workshop was organized and hosted by Alliance for Coastal Technologies (ACT) members at the University of Hawaii at Manoa (UHM) and sponsored by the National Oceanic and Atmospheric Administration (NOAA)/US Integrated Ocean Observing System (IOOS) on May 15 and 16, 2018 in Honolulu, Hawaii. An advisory committee comprised of leading experts who use hyperspectral imaging in coastal waters (Dr. Eric Hochberg, Dr. Karen Joyce, Dr. Sherry Palacios, Dr. Andrea VanderWoude) assisted ACT (Dr. Margaret McManus, Mr. Daniel Schar and Dr. Mario Tamburri) and NOAA (Gabrielle Canonico) in planning the workshop. There were 17 participants from various sectors including: research scientists, technology developers, industry providers and technology users (Appendix A).

The workshop was opened with a presentation about ACT, as well as an overview of the workshop by Professor Margaret McManus (UHM/ACT), after which time the participants were introduced through informal activities led by Dr. Karen Joyce. After the informal introductions, steering committee experts who use hyperspectral imaging in coastal waters (Dr. Eric Hochberg, Dr. Karen Joyce, Dr. Sherry Palacios, Dr. Andrea VanderWoude) gave a presentation on the state of the technology and outlined the goals for the workshop. These presentations were followed by short presentations from each of the workshop attendees. The attendees were asked to introduce themselves, to discuss successes and hurdles they have experienced using hyperspectral imaging, and to discuss how they envision using hyperspectral imaging in the future.

After the presentations, the participants were split into three working groups. Working groups were determined by two steps. First, a random number generator was used to assign groups, second, the groups were then slightly revised by the following criteria: area of expertise, and steering committee representation. The primary objective of break-out group #1 was to answer the question "Why hyperspectral imaging", specifically to discuss current top-level science/management goals and specific objectives. After break-out group #1, the groups reconvened in plenary, and a chair from each group provided a summary of the group's findings. Participants were divided again into three groups for break-out group #2, using the method previously described. The primary objective of break-out group #2 was to answer the question "What is the current status of the technology?", specifically to discuss *current* science requirements, observables, observation requirements.

On the second day of the workshop, the groups from break-out group #2 reconvened in plenary, and a chair from each group provided a summary of the group's findings. Participants were then divided again into three groups using the method previously described for break-out group #3. The primary objective of break-out group #3 was to answer the question "Where do we see the field in 10+ years?", specifically what are the *future* goals, observables, and requirements. After break-out group #3, the groups reconvened in plenary, and a chair from each group provided a summary of the group's findings. After lunch all attendees from the workshop gathered together for break-out topic #4. The primary objective of break-out group #4 was to discuss what a demonstration project would look like. Recommendations from this break-out group are described in detail on pages 20-24 of this report.

WHY HYPERSPECTRAL IMAGING?

The primary objective of break-out group #1 was to answer the question "Why hyperspectral imaging", specifically to discuss current top-level science/management goals and specific objectives. Hyperspectral sensors (either imagery or from a point spectrometer) collect photons within a large number of narrow bands across the electromagnetic spectrum. This radiometric measurement is information-rich compared to the data obtained from a multispectral sensor. Sensing a surface using a multispectral sensor provides a coarse spectrum that provides considerable information about aquatic ecosystems, but potentially misses useful information available in hyperspectral data. Hyperspectral imaging captures the diversity of spectral signatures that can be used to sense a wide range of surfaces, habitats, taxonomic groups, and even changes within all of these over time. Hyperspectral imaging of aquatic targets has the potential to expand our knowledge of dynamic coastal ecosystems, but more data is needed to fully realize the extent of its utility. Importantly, hyperspectral imagery can also be used to emulate multispectral sensors or to apply legacy algorithms and methods, while multispectral imagery cannot infer the rich dataset available from the full spectrum.

To evaluate the question, “Why hyperspectral imaging?” four questions were posed. These questions included; 1) For what fundamental questions is the technology (potentially) useful or necessary? 2) What observations can be made using this technology that can’t be made using other methods? 3) Which methods are complementary to hyperspectral imaging, and how? Finally, 4) What does the non-specialist community want to measure?

For what fundamental questions is the technology (potentially) useful or necessary?

Hyperspectral imaging is uniquely positioned to address certain fundamental questions for aquatic remote sensing that can be used independently or coupled with other methods. These fundamental questions fall into three categories: 1) understanding processes in aquatic ecosystems, 2) informing coastal communities and decision makers, and 3) developing new sensor technology.

Hyperspectral imagery can be used to better understand the biology, physics, chemistry, and geology of aquatic ecosystems. Questions include: What is the biodiversity of aquatic systems (different phytoplankton communities, as well as optically shallow marine habitats)? Can we better understand the environmental mechanisms leading to different types of blooms? What is the health of marine habitats like coral reefs? Hyperspectral imagery may provide critical information for community decision makers for assessing stocks and detecting changes in aquatic ecosystems. Fundamental questions include: How is development (sustainable or not) affecting critical ecosystem services? How are estuarine and other coastal systems changing? What is the material exchange between the land and ocean (sediments, chromophoric dissolved organic matter-CDOM)? What is the bathymetry? How might floating surface material such as plastics, oil, bubbles, nuisance algae, be sensed and monitored? What is the distribution of particular harmful algal bloom taxa?

Hyperspectral imagery can be used in selecting wavebands, producing signal to noise recommendations, improving atmospheric correction and other applications for new sensor technology from the ultraviolet to the short wave infrared on a variety of platforms. Fundamental questions to address this theme included; Which bands and band-widths are optimal for deployment on buoys, submersibles, or drones for different applications? How to better discriminate between aerosols and constituents in the water column?

What observations can be made using this technology that can't be made using other methods?

Hyperspectral imaging permits observations and insights that cannot be made using other technologies. Simply put, hyperspectral imagery contains the information density needed for sophisticated statistical and signal processing techniques and it captures information in such narrow bands that new insights can be made at the physiological and ecological scale. Themes related to information density include: the dense information content of high spectral resolution data is suited for sophisticated methods, like machine learning; the high spectral resolution data provides information for exploratory analysis to find spectral features that may not be noticeable in multispectral data (e.g., elemental ratios in kelp, an index of health); it allows for discrimination when different sets of optical and geometric parameters yield similar "non-unique" multispectral data. Themes related to insights from narrow bands include: identification of unique pigment absorption and fluorescence signatures in the spectra; improved discrimination of different material in the sea surface (phytoplankton taxa, plastics, floating algae, submerged vegetation types, oil, etc.); improved parameterization of visual predator-prey interactions (e.g., comparing the visual perception systems of predators in relationship to the coloration and/or camouflage of their prey); and quantitative analysis of habitats, such as coral reefs, without destructive sampling.

Which methods are complementary to hyperspectral imaging, and how?

Hyperspectral imaging is not the panacea for all coastal and ocean remote sensing insights. In fact, data value is significantly enhanced when combined with coincidental observations using other methods. These fall into three themes; the collection of coincident in situ measurements for verification and algorithm validation, other remote sensor measurements that add value to the radiometric measurements, and application of advanced image processing and statistical methods. As with most ocean and coastal remote sensing, it is necessary to obtain coincident in situ measurements of surface and sub-surface radiometry and the inherent optical properties (e.g., light absorption and backscattering) of the water column. It is important to obtain coincident measurements in both space and time. In-water observations are used for validation as well as to understand other information such as chlorophyll concentration, taxonomy (e.g., genetic, microscopic or via newer methods such as the Imaging Flow Cytobot), physical parameters (e.g., sea surface temperature and salinity), and other water quality parameters (e.g., CDOM and turbidity). Other optical sensor methods provide additional insight into the structure of the water column and benthos (e.g., LiDAR), the ability to remove sun-glint (e.g., polarization measurements), and to detect materials on the surface, such as surfactants (e.g., photogrammetry-type methods collecting imaging from multiple angles over a target). While still within the realm of radiometric observations, the collection of SWIR data to aid in atmospheric correction, the removal of white caps, and to observe material at the water's surface is needed as a standard collection. Finally, within the theme of sensor collection, coincident and geolocated measurements for straightforward geo-referencing of data needs to be standardized for ease in image processing. Sophisticated numerical methods are complementary to hyperspectral imaging because of the information density contained within the data. One of the biggest barriers to the use of hyperspectral data is access to the data and the ability to process it. Another major barrier is inconsistent image data collection and storage protocols that require inefficient duplication of coding and processing effort by many users of this type of data. As new open-source access and processing platforms continue to develop, it is anticipated that hyperspectral imagery and image processing protocols will be included.

What does the non-specialist community want to measure?

This issue of barriers to access (inclusive of the data, the computing resources and programming skills needed for processing) comes up again and again in the hyperspectral community. This issue arises across the range of expertise. It is important to also address the needs of the trained community, as improving access to data and processing is key to delivering information to the non-specialist or "untrained" community in an efficient way. The question, "What does the non-specialist community want to measure?" can be broken down into two themes: what to measure and how to obtain and process the data. Also important is how does the trained scientific community use the non-specialist data in terms of criteria and confidence.

The non-specialist community generally wants a data product of interest (e.g., water quality, habitat type, public health indicator etc.) to support decisions using some standard unit for that data product or a categorical rating system like green, yellow, red, in a portable data file that can be used on an open source platform (e.g., a kmz file). The non-specialist community wants data products that are intuitively understandable and based on rigorous science and have confidence levels associated with them to make sound policy and management decisions. Examples include data products that can be used for environmental change detection, maps of environmental hazards that can be communicated to the general public and used for citizen science efforts, products to enumerate risks to public health, information to quantify environmental services and reports on national objectives (e.g., sustainable development goals). There is interest in on-board processing of hyperspectral data in near-real time and the transmission of derived information to user communities. Technology development in this area will help serve the needs of non-specialist users to receive key data products in a timely manner for decision support. As unmanned survey systems continue to develop, on-board processing of data to a final data products will serve the non-specialist community well.

The non-specialist, as well as the trained, community wants easier access to high-level data products and also low- and high-level processing capabilities. Expertise in hyperspectral data acquisition and processing is hard-earned and exposes many inefficiencies in where data and appropriate data tools can be obtained. The non-specialist user community needs information distilled to file types that are easily viewed either on a website or through the use of standard GIS software (e.g., ArcGIS or QGIS). The non-specialist community includes the people who want easier access to the imagery or data products and the ability to view it in just a few clicks in ArcGIS as a raster layer, or data that has been synthesized into a shapefile. Cloud based image processing (e.g., Google Earth Engine) is gaining popularity and hyperspectral imagery would be a good addition to the data sets and methods available on such platforms. Concerns for developing regions where internet access is slow or not available should be considered when developing these types of tools as cloud platforms may work well for some, but not all communities and high performance computer systems may be required. In addition to cloud computing, the ability to use mobile devices to connect to the cloud to either transmit data to the cloud, obtain data from the cloud, or direct processing of data in the cloud, all in support of research or management decisions, would be helpful to the non-specialist and trained community.

Hyperspectral data sets are typically large and the user community (trained or non-specialist) needs access to a clearinghouse of trusted environmental data and open source tools to work with large volumes of data. Presently, working with hyperspectral data is so specialized and performed in so many different ways that there is a real need to streamline the effort. Once the data are accessible and more straightforward to work with, more users will likely adopt it.

WHAT IS THE CURRENT STATUS OF THE TECHNOLOGY?

The primary objective of break-out group #2 was to answer the question "What is the current status of the technology?", specifically to discuss *current* science requirements, observables, observation requirements. To evaluate this overarching question, nine specific questions were posed. These included; 1) What geophysical parameters are currently retrieved? 2) How accurately are they retrieved? 3) What limits retrievals? 4) What successes have there been? 5) What lessons have we learned? 6) What is the typical workflow for hyperspectral image processing? What is the status of open source tools for image processing? 7) What types of platforms currently support hyperspectral imagers? 8) What are the observational/instrumental requirements for a particular science need? and 9) What is the status of calibration/validation activities?

This section is a synthesis of the breakout questions from each of the groups from both researchers and industry participants. It was also noted that in terms of the hyperspectral sensors that are available, there are some sensors that are more reliable than others but the ideal sensors are costly. With that in mind, reliable and accurate geophysical parameters are highly dependent on the chosen hyperspectral imaging (HSI).

What geophysical parameters are currently retrieved?

Geophysical parameters that are currently retrieved include at-sensor radiance processed to remote sensing reflectance, bathymetry, digital elevation maps of intertidal regions, bottom type, water quality parameters such as algal pigments (e.g., chlorophyll, phycocyanin) fluorescence, and red-edge, color-dissolved organic material, total suspended matter and particle size distribution (although this has a higher uncertainty). Other biological parameters include the presence of sea grasses and kelp beds and the rate of primary productivity. End users typically derive these parameters from the wavelength range of 350 nm through the short-wave infrared range (SWIR: 900 to 1700 nm) and SWIR may be useful depending on the particular application. The spectra derived from the sensors at these wavelengths have different derivatives that lead to geophysical parameters for end users.

How accurately are these geophysical parameters retrieved?

The accuracy of geophysical parameter retrieval depends on sensor characteristics such as spectral width of bands, signal to noise (SNR), spectral sampling, and the ground sampling distance (GSD) in relation to the spatial scales of the features of interest. In general, the higher the SNR, the finer the spectral sampling, and the smaller the GSD, the higher the parameter retrieval accuracy. Airborne hyperspectral sensors typically have high SNR and can be equipped with optics that result in high spatial resolution. However, spatial coverage is small and data collection opportunities are sparse compared with satellite sensors. Satellite sensors, on the other hand, tend to yield regional or global coverage but with lower SNR and larger GSD. Thus, uncertainties associated with parameter retrievals from space are large relative to aircraft sensors. NASA specifies a 0.1 to 0.3% radiometric accuracy requirement for all satellite programs and 5% accuracy for open ocean chlorophyll retrieval. However, this may not be possible for optically complex coastal or inland waters. Airborne campaigns can typically exceed these requirements, but data collection tends to be expensive. There is a baseline requirement for ground-truth data, including radiometry collected with field spectrometers, to validate airborne and spaceborne data. There also needs to be a bench test to tell whether or not the sensor is providing reliable results, when airborne accuracy is not typically reported. In the context of the parameters listed in the previous question, there is a high confidence in total suspended material, bathymetry and depending on the study site, also in phycocyanin and phycoerythrin algal pigments.

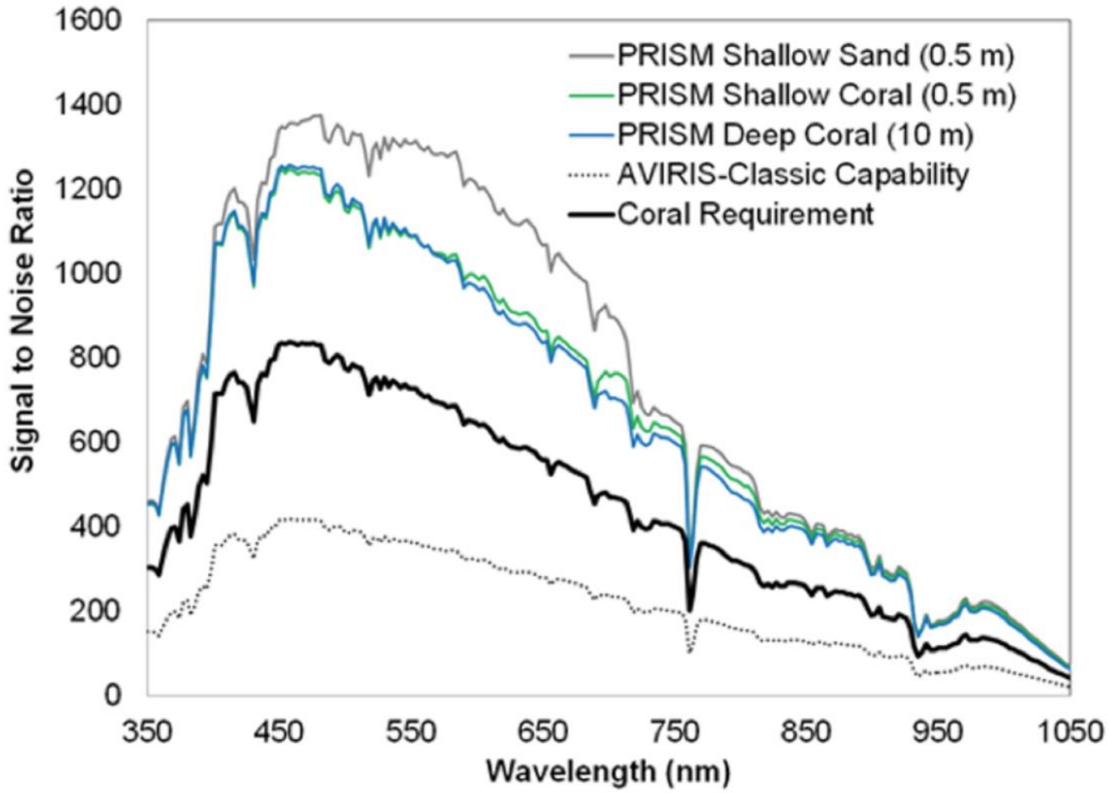

Figure 1. CORAL SNR performance. Requirement set at 2x that of AVIRIS-Classic. Projected performance gives significant margin.

What limits retrievals?

In addition to sensor limitations described previously, the choice of algorithms and atmospheric correction models also influence the accuracy and precision of geophysical parameters. The collection of appropriate, coincident and extensive validation datasets also limits the ability to assess the accuracy of retrievals. The sensor signal to noise ratio effects the retrieval of the geophysical parameters, which is also dependent on how clear the water is (optical properties) and the depth (i.e. whether bottom reflection is part of the signal). Further limitations in retrievals are spatial mixing within a pixel and lack of inherent optical water properties and *in situ* data to compare to the sensor retrievals.

What successes have there been and what lessons have we learned?

One of the lessons learned in satellite-based hyperspectral imaging is that the utility of the imagery is greatly dependent on the initial investment. If the investment in instrument calibration is not conducted up front, it can take years to calibrate, correct artifacts and produce usable and accurate data that can be widely distributed to the research and user community.

A common theme that emerged from the workshop is that better atmospheric correction is critical to retrieving accurate products. This includes better removal of sun glint, reflected skylight and whitecaps from the data, as well as handling absorbing aerosols and gases known to interfere with retrievals in metropolitan areas.

Manned aircraft missions are at the mercy of human and weather constraints. Often, people and *in situ* sensors are deployed only to be informed that the mission has been cancelled. Thus, *in situ* data sets in support of airborne data sets are scarce. An advantage of manned aircraft is that payload capacity is typically much greater than for unmanned airborne systems.

Unmanned airborne systems are rapidly developing and, when available, can be deployed under a much broader range of environmental conditions compared with manned systems, but data quality and uncertainty associated with parameter retrieval is uncertain.

Regarding *in situ* measurements, manned operations are typically limited to a few stations coincident with the remote sensing data. However, such operations are regarded as the gold standard in terms of *in situ* data quality. Unmanned, autonomous *in situ* systems have been employed for several decades in the form of instrumented moorings. These systems, such as MOBY (Pacific Ocean in the vicinity of Hawaii) and BOUSSOLE (Ligurian Sea), deployed in relatively clear ocean water environments have proven valuable for radiometric calibration of satellite systems. Instrumented moorings are useful in that data is collected continuously, thus ensuring matchups with remote measurements, cloud cover permitting. Deploying long-term sensors in productive coastal waters is challenging due to biofouling, although new sensors are available equipped with anti-fouling measures such as mechanical wipers and copper fittings.

Autonomous survey systems are slowly being developed and have been shown to yield high resolution *in situ* observations with increasing parameter diversity. Such systems can potentially result in rapidly collected data sets that are far richer in the representation of environmental conditions than those collected by more labor-intensive manned operations.

What is the typical workflow for hyperspectral image processing? What is the status of open source tools for image processing?

A typical workflow with hyperspectral image processing involves processing the images from raw radiance image cubes to reflectance. This includes a step for atmospheric correction, followed by a chosen application-specific algorithm to pull out the geophysical parameters. Typical tools include Datacube (open source), ENVI with IDL code, QGIS (open source), GDAL (open source) and Python (open source) and software on GitHub (open sources). Other post-processing considerations are for spectrograph properties and camera distortion, sun glint, geometric correction, ground control point (GCP) georegistration and orthorectification where the terrain varies, image mosaicing, masking out clouds and cloud shadows, land masking, and validation of the geophysical parameters.

What types of platforms currently support hyperspectral imagers?

Platforms that currently support HSI include Cubesats such as the SWIS (Snow Water Imaging Spectrometer), as well as the SmallSat CHRIS-PROBA operated by ESA and varying from anything from *in situ* measurements, such as autonomous surface vessels (ASV), to miniaturized sensors deployed on AUVs and sub-orbital or orbital satellites. There is a balance between observational objectives and logistics when considering which platform to use for hyperspectral imagers.

What are the observational/instrumental requirements for a particular science need?

The observational and instrumental requirements for a particular science need are based on clear statements of signal to noise ratio (SNR), bandpass filters, spectral sampling, and GSD appropriate for the geophysical parameters of interest. It is also key to have a narrow bandwidth in some cases and the instrument needs to match the application. There is also a need to compare the hyperspectral sensor with other satellite systems to compare their image retrievals.

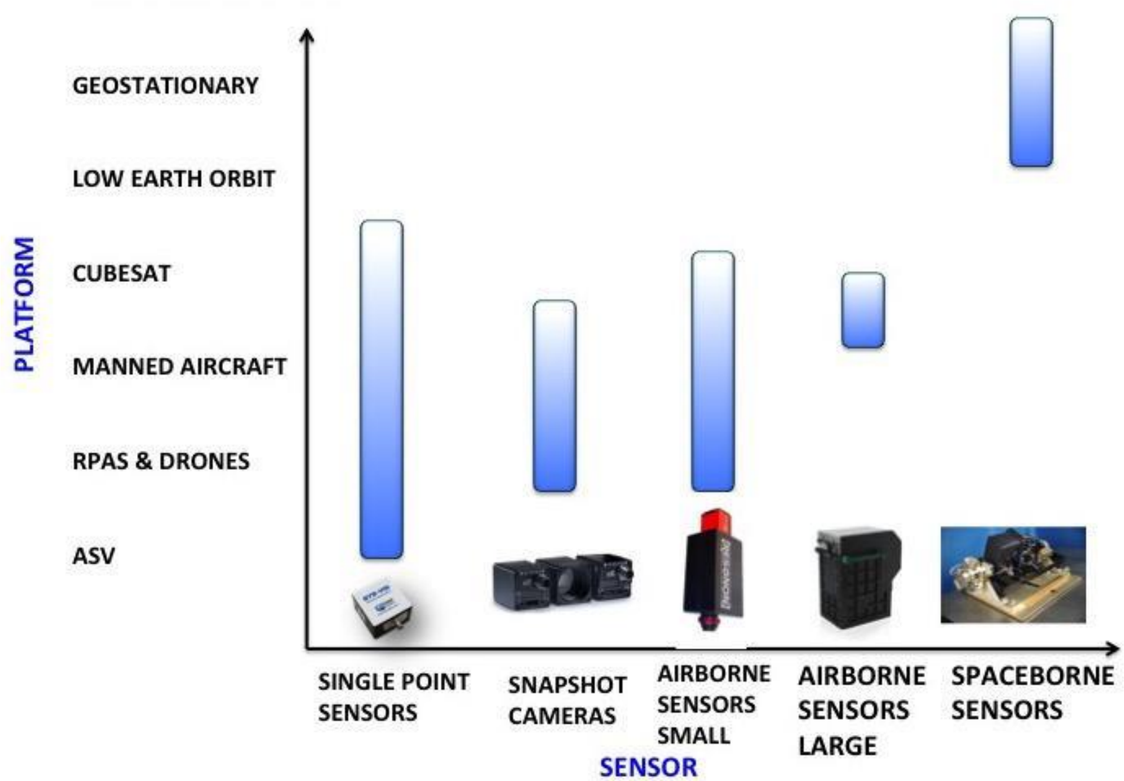

Figure 2. Example of sensor and platform pairings. (ASV - Autonomous Surface Vessel. RPAS - Remotely Piloted Aircraft System) Figure by A. VanderWoude.

Status of calibration and validation activities.

The status of calibration and validation activities for hyperspectral data requires accurate cross-calibration between sensor and instruments used. More importantly, the requirements change depending on the specific application. It was recommended that a target albedo be given to the manufacturers to standardize the calibration model. For validation purposes there also need to be more publically available *in situ* data sets. A model example is the CORAL mission where validation is driven by the geophysical parameter of interest and sampling for validation efforts are representative (i.e., coincident IOP measurements, depth, photos of the bottom substrate). Algorithm development suffers from similar issues in that there is virtually no standardization with calibration and validation. This includes radiometric and geometric calibration of the imaging sensor, as well as in-water collection of geophysical data for vicarious calibration and, ultimately, validation of image-derived observables. A summary table of the available software for radiometric and geometric calibration, as well as typical corrections applied to hyperspectral data is listed below.

THE FIELD IN 10+ YEARS

The primary objective of break-out group #3 was to answer the question "Where do we see the field in 10+ years?", specifically what are the *future* goals, observables, and requirements. To evaluate this question, seven questions were posed. These included; 1) What coastal environmental properties might/should be measured? 2) What accuracy is required? 3) How do we get there? 4) How should automation of image processing be prioritized? 5) How should the difficulties in atmospherically correcting hyperspectral imagery be mitigated? 6) How should calibration/validation activities evolve? 7) What types of platforms should be prioritized?

In order to visualize how the field may look ten years into the future, it is helpful to understand how much things have changed over the past decade. This provides us with a tangible reference period to which we can relate. Perhaps the most obvious example within a technology field is the time that has elapsed since the iPhone was released in June 2007. Without a doubt this disrupted the way we interact with technology and even the way we interact with each other. This advance initiated a whole range of new careers that we never imagined, including app developer, social media manager, social influencer, and Uber driver. It's now hard to imagine what it was like *without* mobile devices and smartphones, yet a little over ten years ago we may not have imagined life *with* one.

With this in mind, we ask what is on the cusp of change or improvement right now that will affect how we do business in 2028+? And how can we put ourselves in a position to benefit from anticipated change and disruption?

One factor that will most certainly have an influence on hyperspectral remote sensing in the future is the growth of big data. With large corporations heavily invested in creating and using big data as part of their daily business operations, the investment (and therefore return) on analytical techniques is far greater than the scientific community alone could have otherwise pushed. Our field will benefit from the data infrastructure, storage capacity, and rapid processing that is developed for commercial purposes. Where previously the sheer volume of data inherent in hyperspectral remote sensing would have crippled servers and processors (and sometimes still does), in ten years time we anticipate that on-board real time processing will be firmly in place.

We are already starting to see more machine learning (ML) and artificial intelligence (AI) come into remote sensing data processing, and this will only increase in line with big data. It will also be the foundation of real-time processing for these massive datasets. The high spatial-resolution data available from remotely piloted systems (under and above water) is particularly suited to ML approaches. However, as with any automated and semi-automated analysis routines, the rule of ‘garbage in, garbage out’ still applies. The challenge faced here for remote sensing is to ensure all data are appropriately calibrated and validated if a valuable baseline is to be set.

While the large commercial players such as ESRI, ERDAS, and ENVI have dominated the software industry in the past, we are increasingly seeing a move towards open source and freely available packages. We expect this trend to continue into the future, which opens exciting opportunities to increase access for analyzing data to those who may have previously been excluded on financial grounds.

October 2018 also marks the ten year anniversary of the Landsat archive becoming freely available. Over these ten years under the open data policy we have seen a proliferation in studies across space and time just by removing the cost barrier. It is only fair to expect that more sources of open data combined with open source software will continue to increase the use of these data for environmental (and other) analyses. Innovation under this scenario is unavoidable.

We have the opportunity to help support such innovation by allowing all data that we acquire to be openly released as well. Indeed, some groups already adopt and promote this practice. However perhaps the biggest challenge associated with open data from different sources is ensuring that it has been collected in a standardized manner if we are to run cross comparisons. Exacerbating this challenge is the sheer volume of sensors, platforms, and operators that are now entering the market. Consumerism has driven technology to develop and deploy sophisticated sensors within our smartphones, so remote sensing data acquisition is now at the fingertips of the average citizen scientist. It is reasonable to expect that the current RGB cameras in our phones will evolve to contain multispectral and even hyperspectral sensors within the next ten years. Once more, calibration, validation, and statements of accuracy become critical.

To ensure our datasets are valid into the future, we must invest in systems and processes for robust data acquisition and processing. We need algorithms that strike the balance between scientific validity and ease of use if they are to be widely adopted. We envision networks of calibration sensors/facilities suited to radiometric, geometric, and atmospheric corrections. These will be supported by applications that can ingest correction factors and apply them to newly acquired data without intensive user interaction.

Finally, remote sensing systems are rapidly becoming available on a personal level in the form of user-generated data from miniaturized sensors, such as high definition RGB cameras, deployed on small drones. Examples in industry include owner-operated systems to inspections pipes, assess the health of farm crops, and survey construction sites. Today, a system costing on the order of $1,000 comes equipped with mission planning software, autopilot and rudimentary obstacle avoidance, and a selection of sensors, both passive and active (e.g., IR LIDAR). Drone technology is advancing rapidly. Several airframes are capable of landing on and taking off from water and at least one version, under development at the University of Pennsylvania, is capable of submerging to a prescribed depth. Several companies have started offering drone-compatible hyperspectral sensors that are self-powered and include limited data storage, such as the Headwall Nano-Hyperspec sensor (http://www.headwallphotonics.com). The two primary weaknesses of drone-based remote sensing are mission duration due to battery storage limitations and sensor noise. However, it is expected that within the coming decade, driven by increasing climate-related demand for localized, high quality, real time data, both of these problems will be largely overcome.

DEMONSTRATION PROJECTS

The primary objective of break-out group #4 was to discuss possible demonstration projects that ACT might undertake. All workshop participants met together in a single group for this discussion, rather than in small groups. As a guide, eight overarching questions were posed at the outset: 1) Where should a demonstration occur? 2) Why should a demonstration occur in a given locale? 3) What geophysical parameters should be targeted? 4) What ground/water validation should be undertaken? 5) Which instrument(s) should be used? 6) Should geometric and radiometric calibrations be undertaken, and to what accuracy? 7) How should flight logistics be undertaken (i.e., planning, airport(s), FBO(s), aircraft, clearance, instrument install, flight engineer(s), pilots, instrument uninstall)? and 8) What image data processing and analysis should be undertaken?

In the end, not all of these questions were directly addressed. Instead, the workshop group naturally gravitated toward developing concepts for a series of four useful activities that could be shepherded by ACT. These activities are described here, in general order of increasing complexity and cost.

A. Processing algorithm round-robin. Remote sensing of the coastal zone, especially via hyperspectral imaging, currently lacks standardization. This includes, but is not limited to, sensors, radiometric calibrations, geometric calibrations, geophysical variable choices, field validation, and algorithms. Of course, the specific algorithms chosen for a project depend on the geophysical variables to be retrieved from the remote sensing data, but even within a single application area (e.g., coral reefs, harmful algal blooms (HABs), kelp forests etc.), there are numerous competing approaches. Thus, while hyperspectral remote sensing is taking a step toward routine deployment, it still has one foot firmly planted in the realm of research and development.

The goal of this demonstration activity is to evaluate capabilities and maturities of different algorithms. Each participant would receive the same data set and attempt to achieve the same objective(s). The data set would comprise calibrated hyperspectral imagery and ground/water validation data. These could be existing real data, airborne or in-water, as collected during any number of recent projects (e.g., CORAL, HyspIRI). Alternatively, the data could be simulated via radiative transfer modeling (e.g., Hydrolight/Ecolight, MODTRAN, 6S). The former has the benefit of representing real-world conditions, while the latter has the benefit of knowing exact values for all geophysical parameters of interest (i.e., perfect and complete validation data).

Designated algorithm objectives might include assessment of water quality and phytoplankton diversity, quantification of coral cover, determination of seagrass leaf area index, and/or minimizing error in atmospheric correction. Based on ecological or physical understanding of the system to be studied, broad objectives would be defined *a priori*, and participants would implement their algorithms to meet those objectives. Participants would be welcome to demonstrate capabilities beyond the stated objectives, as well.

To be most widely useful, it would be desirable to make all submitted algorithms open-source. However, it is recognized that vendors may not wish to share their valuable intellectual property. As a result, it is expected that most participants will be users themselves, e.g., researchers or resource managers.

B. Mooring calibration/validation of hyperspectral remote sensing. In-water data for optical calibration and validation of hyperspectral imagery are sparse. Further, observables and measurement methods are not standardized across the field. The aim of this demonstration activity is to assess various *in situ* sensing methods, such as hyperspectral radiometers and absorption and scattering meters, in complicated coastal waters in the context of providing data for comparison against hyperspectral imagery. In this case, however, no remote sensing data are required; this is a purely in-water (or water surface) activity.

The objective is to mount multiple versions of key sensors on an in-water mooring, optimally partnering with Integrated Ocean Observing System (IOOS) moorings. The sensors could be set up to collect measurements over prescribed time periods, including:

- in-water upwelling radiance (L_u);
- water-leaving radiance (L_w) both with and without skylight blocking
- downwelling irradiance (E_d), either above the water [$E_d(0^+)$] or at depth [$E_d(z)$]; or
- various water inherent optical properties (IOPs), such as absorption (a), scattering (b), backscattering (b_b), and the volume scattering function (β).

An important derived parameter would include remote sensing reflectance [$R_{rs} = L_w \div E_d(0^+)$], which is used (1) to evaluate accuracy of atmospheric correction and (2) as primary input to subsurface retrieval algorithms. Inclusion of $E_d(z)$ for at least two depths and/or some subset of IOPs is important for validation of subsurface retrieval algorithms. Some thought needs to be put into this experiment because presently there is no standard that is considered "truth." The parameter R_{rs} is a generally a derived parameter made either below the sea surface or from an above water sensor. Artifacts occur in all measurements made of $R_{rs.}$ Most comparisons are evaluating precision of the measurement rather than accuracy of the measurement.

One example of an existing, operational remote sensing calibration/validation mooring is MOBY (www.mlml.calstate.edu/moby/). This system has provided vicarious calibrations to ocean color satellites, including SeaWiFS and MODIS, since 1997. MOBY's primary products are direct measurements of $E_d(0^+)$ and derived estimates of L_w. However, our proposed demonstration would be directed at more optically complex coastal waters, for which MOBY would be of limited value.

This demonstration activity would have the ancillary objective of assessing how best to deploy the given instruments. If hyperspectral overflights are occasional and *ad hoc*, then the calibration/validation system would only need to be deployed during flight operations. This means that sensors could be calibrated and maintained in the long periods between flights. Conversely, if hyperspectral overflights are routine, for example, on a weekly basis, then the calibration/validation system would require rapid turnaround for any laboratory calibrations and maintenance. However, it should also be emphasized that the optimum duration of sensor deployment under various coastal conditions is a largely open question. And, the uncertainties in R_{rs} derived under different water and sky conditions have yet to be quantified.

C. Controlled observations in tanks/mesocosms. A basic problem with evaluating remote sensing data is a lack of comprehensive ground truth information. Even extensive field efforts can lead to only a few useful match-ups between near and remote observations. The aim of this demonstration activity is to bring the remote sensor near to the system being observed. Importantly, the target is under controlled - or very well characterized - conditions. Experimental habitats could be constructed in a laboratory setting, either indoors or outdoors, using large tanks/mesocosms. These would allow for exact experimental manipulation of water depth, water optical properties, and "seafloor" composition (Example tanks can be seen at the Australian Institute of Marine Science's National Sea Simulator; www.aims.gov.au/seasim, additionally AQUACOSM has 21 experimental mesocosms in freshwater and marine areas in Europe www.aquacosm.eu). Remote sensing systems could be "flown" over the tanks via a boom system (e.g., Caras & Karnieli, 2015). Resulting data would allow for rigorous intercomparison of sensor types and processing algorithms. The potential uncertainties of the optical measurements from a tank environment would have to be estimated using Monte Carlo models or other radiative transfer simulations.

Similar experiments could be performed utilizing even larger outdoor ponds, e.g., where each pond has a different, but well characterized, algal density or community assemblage. (There are some natural analogs that have widely varying optical characteristics over a relatively small spatial region, such as the South Bay Salt Ponds near San Francisco.) Such experiments may have less artifacts than tank mesocosms. Hyperspectral imaging sensors could be deployed via boom or low-flying aircraft (autonomous or piloted). Again, resulting data would allow for rigorous intercomparison of sensor types and processing algorithms.

Any participants with a hyperspectral sensor suitable for attachment to the boom or aerial vehicle could be included in the experiment. In either controlled mesocosms or outdoor ponds, it would be critical that all sensors be properly calibrated to the same NIST-traceable standard (e.g., integrating sphere or calibration lamp plus Spectralon® reference), to ensure standardized comparisons. It is not necessarily required that sensors be imagers; single-point spectrometers can also potentially provide useful ecosystem and habitat data.

D. Flight comparison with PRISM as standard. This is the most conceptually straightforward demonstration activity: conduct an actual hyperspectral remote sensing mission to evaluate the entire process. In practice, such a mission is actually complicated and expensive, including (but not limited to) flight planning, engineering, flight operations, sensor radiometric/geometric calibration, atmospheric correction, water column inversion to desired geophysical variables, and in-water validation. Additionally, some hyperspectral imaging systems are more "turn-key" than others.

The aim would be to utilize as many different hyperspectral systems as logistically (and financially) feasible, including the newest miniaturized sensors fielded on autonomous drones. The Portable Remote Imaging SpectroMeter (PRISM), developed and operated by NASA's Jet Propulsion Laboratory, could serve as the current top-quality standard against which other sensors could be compared, but this is not required if consensus was reached regarding another sensor. Installation and operation of hyperspectral imagers on an aircraft requires a team of several people (not including pilots), and additional personnel are required for ground operations, image data post-processing, and image analysis. The PRISM instrument, for example, can currently only be flown in a few types of aircraft; most pertinent to ACT would likely be the DHC-6 Twin Otter (for example www.twinotter.com/aircraft.htm). Many of these aircraft do have capability to carry multiple instruments at one time. If this course were chosen, the field portion of the project should be given ample time to account for weather delays and the project should be conducted in water bodies for which there is ample sensing capability already in place in addition to historical data. Moreover, the ideal would be to fly over a very well characterized site that has established field validation sites, ground control points, aerosol monitoring nodes, and known benthic features, if applicable.

Another strategy to make data collection as cost effective as possible would be to leverage flights of opportunity. These could include:

- Flights undertaken for the NASA Student Airborne Research Program (www.nasa.gov/centers/ames/earthscience/programs/airbornescience/studentairborneresearchprogram);
- Research and development flights supporting NASA's upcoming Surface Biology and Geology satellite mission (SBG, related to the former HyspIRI; hyspiri.jpl.nasa.gov); and
- Ongoing data acquisitions by either manned or unmanned aircraft.

A final approach suggested by the workshop would be to install PRISM on NASA's high-altitude ER-2 aircraft (www.nasa.gov/centers/armstrong/news/FactSheets/FS-046-DFRC.html), then by wide invitation, solicit vendors to perform their own data acquisitions concurrently to the ER-2 flight(s). These airborne activities would be accompanied by comprehensive ground/in-water measurements to provide necessary validation of all processing and analysis steps (e.g., atmosphere correction, geophysical variable retrieval).

SUMMARY AND NEXT STEPS

The recommendations emerging from this workshop include a list of possible demonstration projects that ACT might undertake. These demonstration projects are listed in order of priority:

1) ***An algorithm round-robin with outside participants using a hyperspectral image data set from varying coastal environments with available in-water validation data (i.e. harmful algal blooms, corals, kelp beds etc.)***
2) ***Mooring calibration/validation of hyperspectral remote sensing with a set of hyperspectral optical sensors deployed on moorings along with coincident flyovers with a hyperspectral imager(s)***
3) ***Controlled mesocosm(s) tank experiments with a suspended boom to 'fly' manufacturers hyperspectral imagers over the tanks to show the imagers capabilities***
4) ***Flight comparison with a sensor like PRISM as a standard.***

In addition, the workshop attendees suggested several venues to disseminate this information: 1) dissemination of the ACT report summarizing this workshop, 2) a town hall at an international conference like Ocean Optics, 3) a webinar, and 4) a manuscript in a peer-reviewed journal.

Dissemination of the ACT Report

This ACT report will be publically available on the ACT website (http://www.act-us.info). The following are ideas of where to bring community attention to the workshop and report:

- International Ocean Colour Coordinating Group (IOCCG).
- Integrated Ocean Observing System (IOOS).
- HyspIRI Science and Applications Workshop in 2019
- OceanObs 19: While the community white paper deadline for OceanObs 19 meeting has already passed. There will be another request for abstracts for posters, and this could be a good venue for results from this workshop
-WHISPERS (Workshop on Hyperspectral Images and Signal Processing – Evolution in Remote Sensing).
- Fulbright-sponsored workshop on hyperspectral remote sensing hosted by Dr. Dierssen at the Flanders Marine Institute in Belgium June 2019 with potential travel expenses supported by Euromarine and OCB.

Town Hall Meeting

For the Ocean Optics Meeting, Dr. Turpie has already proposed a town hall on coastal and inland waters. It may be possible to include some discussion from the Hyperspectral Imaging of Coastal Waters Workshop in this town hall, even if it is simply a pointer to the report. Dr. Dierssen is also presenting a Town Hall on Validation of Phytoplankton Community Structure at the Ocean Optics meeting and can present an overview of the workshop findings.

Webinar

Dr. Anstee and the Earth Observation Community in Australia do webinars on a monthly basis that are generally well attended - this type of report would be of interest.

Peer-Reviewed Manuscript

Workshop attendees agreed to check in again after writing the report. This type of information might be appropriate as a ‘state of the science’ manuscript.

The final discussion the group held regarded identifying a “broader community” (i.e., K-12 students and teachers, individuals who rely on coastal data to make management decisions, interested citizens) that might benefit from this work. More thought needs to be put into how to reach these individuals.

REFERENCES

Caras T, Karnieli A (2015) Ground-level classification of a coral reef using a hyperspectral camera. *Remote Sensing* 7:7521-7544

APPENDIX A: WORKSHOP ATTENDEES

Picture facing page. Attendees left to right, *Daniel Schar, Steven Ackleson, Raphael Kudela, Margaret McManus, John Merrill, Karen Joyce, Heidi Dierssen, Erin Hestir, Kevin Turpie, Andrea Vander Woude, Jan Newton, Sherry Palacios, Janet Anstee, Samantha Lavender, Jason Howse, Rodrigo Garcia, Eric Hochberg.*

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