Roadmap towards a distributed and operational pelagic imaging network

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Targets of pelagic imaging

In principle, all particulate objects floating, sinking or swimming in ponds, rivers, lakes and the ocean (particles, plankton, fish, plastics, whales etc.) are targets of pelagic imaging. Imaging of individual organisms and particles, as long as the volume analyzed is well quantified, makes it possible to obtain simultaneously: (1) abundance of the different groups of plankton and their relative contribution to total abundance and biomass as well as the assessment of plastics pollution, (2) morphological or optical characteristics of the organisms that can be used to obtain their biovolume as a proxy of their biomass, to derive size spectra of the imaged objects and other functional traits (3) contextual information on individual behavior or life cycle traits (e.g., reproduction, parasitism, predation) that can be used to analyze ecological processes, and (4) production of a digital archive of images and optical properties that can be shared or reprocessed if more information is needed. In addition, imaging systems can be operated on samples obtained with nets and bottles or with *in situ* camera systems. *In situ* imaging has the advantage of being non-destructive. Net sampling yields concentrated samples, and these samples can be imaged immediately after catch or fixed for later processing (Lombard et al., 2019). Pelagic imaging can provide environmental indicators such as plankton community composition or biomass, which are needed to monitor aquatic ecosystems (Giering et al., 2022). Different imaging systems (Planktoscope, ZooScan, FlowCam, ISIIS, IFCB, Cytosense, CPICS, LOKI, UVP5, UVP6, among others) are needed to cover the entire size range from microscopic plankton organisms to fish. The capacity to assess plankton with imaging systems increases the temporal and spatial resolution attainable when compared to classic studies where humans identify and count the organisms or other targets. Pelagic imaging yields lower taxonomic resolution than such an approach, but can provide other trait information (size distribution, developmental status, symbiotic interactions etc.). The recent and ongoing development of *in* *situ* imaging technologies that can be deployed at large scales on autonomous platforms, coupled with artificial intelligence and machine learning (AI/ML) for image analysis, promises a solution to overcome the practical limitations of traditional collection and analytical methods (Giering et al., 2022) and opens up new ways for research and ecosystem management.

Pelagic imaging for research and ecosystem management

Laboratory-based and *in situ* imaging instruments now generate information on plankton and particle abundance, diversity and size distribution with an unprecedented sampling frequency, comparable to that achieved with environmental probes and orbital sensors. Underwater camera systems can be remotely operated from research vessels, on autonomous floats or connected to mooring arrangements to perform observations at relevant spatial and temporal scales. This has led to a revolution in the way we interpret marine ecological processes because instead of integrating plankton diversity, abundance and biomass across depth layers or long time intervals, as achievable with traditional plankton net sampling, researchers can now "see" the aquatic world with much higher resolution than before.

Practical applications of *in situ* imaging systems to characterize aquatic ecosystems and help understand and mitigate environmental impacts are widespread. For instance, the Imaging FlowCytobot (IFCB) has been operating in the Gulf of Mexico for more than 15 years, capturing high-frequency images (at ~20-minute intervals) to generate data on microplankton community composition (Fiorendino et al., 2021). This has provided important early warning information on the advection of toxic microalgal blooms towards aquaculture sites, preventing seafood consumption, and thus public health issues and economic losses. The Underwater Vision Profiler (UVP, Picheral et al., 2010, 2022) has been applied worldwide for more than a decade (Kiko et al., 2022) to estimate particle vertical flux and its influence on the carbon pump, yielding crucial data on biogeochemical cycles (Clements et al., 2022). Potential impact of global climate change on marine ecosystems has been investigated using a lab scanner (Beaugrand et al., 2019). In the offshore fisheries industry, pelagic imaging has been used to perform fish counts and species identification during net trawls, enabling the acquisition of distribution data at fine scales for better interpretation of acoustic results (Allken et al., 2021). Salmon aquaculture facilities in Chile apply regular monitoring of algal blooms and potential pests using the benchtop FlowCAM, an imaging flow cytometer and microscope (Mardones et al., 2022). In addition, imaging acquisition tasks can now be carried out with low-cost instruments such as the recently developed Planktoscope (Pollina et al., 2022). Combined with other contemporary approaches in aquatic research, such as genomics and acoustics, pelagic imaging will certainly continue to deliver important insights on the status and development of aquatic environments for decades to come.

However, the new avenue of research opened by pelagic imaging still needs to reach a wider community of scientists, stakeholders and decision-makers. The global south is particularly underrepresented in the pelagic imaging community, a problem demanding efforts in capacity building and technological advances towards more affordable instrumentation. In another perspective, public and private companies are required to carry out environmental impact assessments for licensing purposes in many countries, but imaging is not included in the methodological provisions to be strictly followed in accordance to the environmental law. For instance, when species-specific biodiversity indices are required, traditional microscopic techniques are the only option to analyze samples and thus monitoring is circumscribed to plankton net tows at very low temporal and spatial resolution. However, suitability of pelagic imaging for such monitoring purposes has been demonstrated in the open and coastal oceans(Romagnan et al., 2016; Lombard and et al., 2019; Pitois et al., 2021). With the recent development of instruments, data software and recognition algorithms (Irisson et al., 2022), some key locks for widespread application of pelagic imaging have been technically resolved. Pelagic imaging - possibly combined with genetic approaches - can lower the costs and increase the resolution for environmental monitoring as a high degree of automation can now be attained.

Several scientific communities spread in different continents have initiated regional, disciplinary (phytoplankton, or zooplankton) or instrument specific networks that are already used in monitoring programs (Campbell et al., 2013; Benedetti et al., 2019). Few international coordination attempts have been made in the past, for example through the establishment of SCOR groups, with the development of open-access internet repositories (ecotaxa.obs-vlfr.fr) and datasets (Kiko et al., 2022), the organization of international training opportunities (AtlantEco, PIQv) or the development of databases that combine different instruments (PSSdb; https://www.st.nmfs.noaa.gov/copepod/pssdb/). However, the user communities of the different imaging devices (e.g. IFCB, UVP, Flowcam, PlanktoScope, Zooscan) are often not formally organized and in particular they are not interconnected. Hence, these spread networking efforts will obviously benefit from further communication that would make protocols, instrument descriptions, QC procedures, data analysis repositories and databases interoperable and accessible for all users. However, the concept of a distributed and operational pelagic imaging network goes beyond such simple communication.

Characteristics of a distributed and operational pelagic imaging network

The goal of a distributed network is the sharing of resources, to accomplish a common objective (Balda, Braveem, 2015; Srinivasa and Muppalla, 2015). In a strict sense, “distributed network” is a term from computer science that describes a network of interconnected computer networks, which are orchestrated to deliver a final data product or service. For our purposes, we can extend this concept to also include digital pelagic imaging devices. Operational oceanography aims to provide routine oceanographic information needed for decision-making purposes and depends on sustained research and development. A multi-platform observation network, a data management system, a data assimilative prediction system, and a dissemination/accessibility system are the core components of operational oceanographic systems (Davidson et al., 2019). The time lag between data acquisition and product provisioning needs to be short enough to enable decision making at the necessary time scale. Hence, for pelagic imaging approaches this needs to be on the order of hours to weeks, if we aim to catch and react to the high frequency and short time events occurring in the ocean (frontal dynamics of eddies, harmful algal blooms, processes related to ebb and tide). Currently, such a time lag is reached in only a few cases (UVP6 on Argo floats, phytoplankton monitoring using the Imaging Flow Cytobot). In most other cases, it takes several months to years for the data obtained with an imaging device to become publicly available, and such data might not be converted into indicators suitable for decision making. Further digitalization of the entire pipeline from image to open access data and the automation of data aggregation and modeling tools will enable us in the near future to deliver products for decision makers that are based on several different, distributed imaging techniques (e.g. covering different size-ranges and stemming from different research groups), possibly even integrated with other environmental sensor data. Once the framework is established, users (scientists and monitoring agencies) can select an imaging strategy adapted to their context, but can also automatically contribute with their datasets to a wider context and thereby benefit research and society in several ways. As a first example, mesoscale plankton dynamics can be studied using a UVP6 - lp mounted on a BGC Argo float (Picheral et al., 2022). However, as the data is collected and made available via an open access server system, it can also be included in global datasets and hence benefit the global carbon cycle assessment. Further developing and interfacing the different spread pelagic imaging networks with this first prototype of an operational pelagic imaging platform could lead to the envisioned distributed and operational pelagic imaging network.

How can we realize a distributed and operational pelagic imaging network in the near future?

To reach the goal of a Distributed and Operational Pelagic Imaging Network, we first of all need the pelagic imaging research community to embrace this concept and to commit to the open science approach of operational oceanography. In particular, data needs to be released directly after recovery. To enable this, funders need to recognize the extreme value of pelagic imaging approaches and the added value of an operational pelagic imaging network. It will increase the value of funding that goes into individual imaging approaches, as it promotes the connected reuse of data and hence provides higher level products. However, this distributed network requires support for coordination, development, maintenance and infrastructure that funding agencies need to consider.

We recommend the following voluntary activities that will pave the way towards a distributed and operational Pelagic Imaging Network:

- Promote discussions at all levels - international, local, high-level, informal - on the current status and future of pelagic imaging in marine and freshwater environments.
- Raise awareness for the importance of plankton for global food security, ocean health and global biogeochemical cycles

- Further develop imaging instruments and server hardware via the integration of technological improvements in camera and computer development. Backwards compatibility should be considered during these developments, to e.g. enable the maintenance and consistency of long-term time series.
- During development, prioritize the establishment of low-cost approaches (such as the PlanktoScope), which will increase applicability in developing countries, for citizen scientists and generally can result in widespread adoption of pelagic imaging techniques. The inter- and intra comparability of new instruments, their data processing tools and data output should also be considered.
- Further develop data pipelines that enable the fast/automated processing and upload of image data to central server systems or archives. These server systems/archives should also enable the automated download of images and/or data by higher level network components.
- Establish and maintain repositories for best practices guidelines, processing software, benchmark image datasets, research datasets and derived products. A first collection of such tools can be found at https://www.aa-mari.net/i-itapina-online-resources/.
- Train the next generation of scientists, not only in the use of single imaging devices, but also teach how different image datasets can be merged and how artificial intelligence and network tools can be used to process the data.
- Consider and enable the integration of imaging data with other data types, in particular environmental data such as temperature, salinity, oxygen concentration and nutrient levels, but also other data types such as genetic data should be archived together, or linked with the image data.
- Develop pelagic imaging based environmental indicators and products to reduce the costs and increase the spatial and temporal resolution of environmental monitoring approaches.

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BUILDING AN ALL ATLANTIC
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