Remote Sensing for Marine Spatial Planning and Aquaculture

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Abstract

This text is part of the introduction to a Masters-level course in 'Planning and Managing the Use of Space for Aquaculture' made by the AquaSpace project. It introduces the use of Remote Sensing in Marine Spatial Planning and site selection for aquaculture. Brief case studies illustrate the aquacultural utility of satellite remote sensing of the coastal waters of the Algarve, the northern Adriatic Sea, and a bay in northern France; a case study in Nova Scotia illustrates the use of low altitude imaging. An exercise involves the use of the ESA SeNtinel Application Platform (SNAP) software.

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1 Unit Study Guide

This text was written during the H2020 Aquaspace project (2015-2018, contract no. 633476) for a Masters-level course in 'Planning and Managing the Use of Space for Aquaculture'. The course consists of a number of units; this unit provides an introduction to the use of Remote Sensing in marine spatial planning for aquaculture.

The unit comprises a text (the document you are now reading), a set of slides, required further reading, and some exercises. The text complements the slides, which can be used as the basis for a class-room lecture. The reading provides details of case studies. The exercises illustrate some of the methods used in processing remotely sensed data

The learning outcomes for this unit are to be able to

- demonstrate an understanding of Remote Sensing of the marine environment and its use for the spatial planning of Aquaculture;
- explain and critically discuss at least one application of Remote Sensing for aquacultural site selection or management;
- apply skills in the processing of remotely sensed data, using at least one freely available software package

2 Remote Sensing

Remote sensing is the science of obtaining information about objects or areas from a distance, typically from aircraft or satellites. Remote sensors collect data by detecting either passive or active energy that is reflected from Earth.

Passive sensors respond to external stimuli in the form of natural energy that is reflected or emitted from the Earth's surface. The most common source of radiation detected by passive sensors is reflected sunlight.

Active sensors use internal stimuli to collect data about Earth. For example, a laser remote sensing system projects a laser onto the surface of Earth and measures the time that it takes for the laser to reflect back to its sensor.

Early passive sensors were essentially cameras, and these are still used for example to provide the basis of the maps used by Google etc. Sensors for sea-surface temperature or ocean colour mostly use a scanning mechanism, whereby visible and near-IR light from strip of planetary surface is imaged along an array of photodiodes, usually after splitting into several colours plus infra-red. A picture of the land or sea is built up as the satellite advances along its track.

There are numerous technical challenges in interpreting data provided by sensors onboard satellites. These include compensating: for the signal absorbed or added by the atmosphere; for the influence on upwelling light leaving the sea surface by the reflection from the bottom in shallow waters; for the absorption and scattering effects of various suspended and dissolved water components; for the influence of the water itself (IOCCG, 2000; Pozdnyakov and Graßl, 2003); for the rapid changes in signal at the land-sea boundary; and for the roughness of the water surface. These influences on water-leaving light have to be corrected by 'sea-truthing' of the remote sensing measurements against observations from ships or moorings before they can used to derive the water products from remote sensing measurements (e.g. chlorophyll a concentration, suspended particulate matter) (IOCCG, 2000).

3 Missions and sensors

Airborne remote sensing of ocean colour has a long history. In his book, 'The Open Sea', Hardy (1956) refers to "a sharp line separating the green water of the English Channel from the deep blue of the Atlantic" that he observed from the air in 1923. In the early 1970s oceanographers used sensing of sea-surface temperature, based on infra-red emission measured by low-flying aircraft, to fix the locations of tidal mixing fronts in coastal waters (Simpson and Hunter, 1974). Aircraft sensing was soon extended by images (Simpson et al., 1978) from satellites flown by the US agencies NASA and NOAA. The discovery of these fronts changed understanding of the physical and biological dynamics of seas on continental shelves (Holligan, 1981).

The first ocean colour sensor, the CZCS, was flow by NASA between 1978 and 1986, and allowed mapping of chlorophyll in coastal waters, such as the North Sea (Holligan et al., 1989). It was followed by the SeaWIFS sensor carried on the SeaStar satellite (1997-2010), and then by the MODIS sensor carried on several NASA satellites, including EOS PM-1 (now Aqua) launched in 2002. Increasing numbers of spectral bands allows better estimation of the 'optically active constituents' in seawater, especially chlorophyll in nearshore waters where the optical signal is made complicated by that from suspended solids and dissolved 'yellow-substances' from freshwater.

A large number and variety of Earth observation satellites are currently in orbit, placed there by government agencies and private enterprise, and serving a variety of purposes: including: military; weather forecasting; observation of land and sea. We focus here on European sensors measuring properties of coastal waters relevant to aquaculture.

The European Space Agency (ESA) was founded in 1975. Envisat was launched 2002 into polar orbit, and ceased functioning in 2012. Sensors included MERIS (MEdium Resolution Imaging Spectrometer, measuring Earth reflectance in 15 bands of visible and near-infrared light). The subsequent Copernicus programme comprises a sequence of Sentinel missions, each with paired satellites in a variety of orbits.[1]

Sentinel-1 is a polar-orbiting radar imaging mission, with the first satellite launched on the 3rd April 2014 (Sentinel-1A) and the second on the 25th April 2016 (Sentinel1-B);

Sentinel-2 is a polar-orbiting multispectral imaging mission covering mission covering land as well as coastal waters, the first satellite was launched on 22nd June 2015 and the second on the 7th May 2017;

[1] Notice the distinction between programme, mission, platform (satellite or aircraft) and sensor.

Sentinel-3 is a polar-orbiting multispectral imaging mission with observations focusing on the oceans to include sea-surface topography, temperature and ocean colour; the latter uses OLCI (the Ocean and Land Colour Instrument). The 3A satellite was launched on the 16th February 2016, with Sentinel-3B planned for launching in April 2018.

4 Optically Active Constituents

The Optically Active Constituents (OAC) of seawater are the components that scatter, reflect, or absorb underwater light, thus contributing to the amount and colour of sea-leaving radiance. They are:

seawater itself

phytoplankton pigments especially chlorophyll but including carotenoids and phycobilins

SPM or Suspended Particulate Matter, both living and non-living

CDOM or Colour Dissolved Organic Matter or 'gelbstoff'

These interact in complex ways to change the colour, amount and angular distribution of light, as photons penetrate into the ocean (e.g. Bowers et al., 2000; Devlin et al., 2009). They also affect the small fraction of photons that is diverted from a downwards course and so leaves the sea in an upwards direction. It is by comparing the colour and amount of sea-leaving radiance with that of sunlight falling on the sea-surface, that it is possible to estimate the concentrations of the OAC.

Doing so requires complex calculations, combining measurements of light at several wavelengths, after correction for absorption and scattering in the atmosphere through which a satellite views the sea.

5 Remote Sensing and Aquaculture

Remote sensing can provide information about the distribution in space and time of many properties relevant to aquaculture. These properties include

- chlorophyll concentration, allowing estimation of food for shellfish and observation of the occurrence and spread of Harmful Algal Blooms;
- sea-surface temperature, which controls the growth rate of organisms

Although the costs of launching and maintaining satellites is high, they can be spread over many users. In addition, some data from satellite remote sensing is in the public domain, providing a low-cost way for developers and planners to plan, monitor, manage and rationally exploit marine resources.

The remainder of this text, and the corresponding slides, exemplify some of the uses of remotely sensed data for the management and spatial planning of aquaculture and the monitoring of environmental conditions relevant both to aquaculture and to marine ecosystem health in general. The exercises suggested in section 10 and appendix A provide an introduction to obtaining and processing such data.

6 Case Study: Algarve

The expansion of aquaculture is a strategic priority for the Portuguese government to improve the use of the extensive exclusive economic zone occupied by Portugal (Governo Portugal, 2013). Marine Spatial Planning, involving the linking of Remote Sensing images with Geographical Information Services (GIS), has been used to define areas off the Algarve coast that are available for developing aquaculture (Fig. 1). This development has to comply with national and EU legal requirements for coastal areas. These include

- the Marine Strategy Framework Directive (MSFD), aiming to prevent the deterioration of the coastal and oceanic ecosystems by requiring monitoring for, and maintenance of, *Good Environmental Status* (GES);
- the Maritime Spatial Planning Framework Directive (MSPFD), aiming to regulate the human uses of these waters.

Christina et al. (2015) used Algarve coastal waters, near Cape Saint Vincent and the town of Sagres, as a case study to test how MERIS Algal Pigment Index 1 (API1) could contribute to the monitoring for the *Good Environmental Status*(GES). The MERIS product extracted was the API1 that corresponds to the total concentration of chlorophyll *a* and its degradation products.

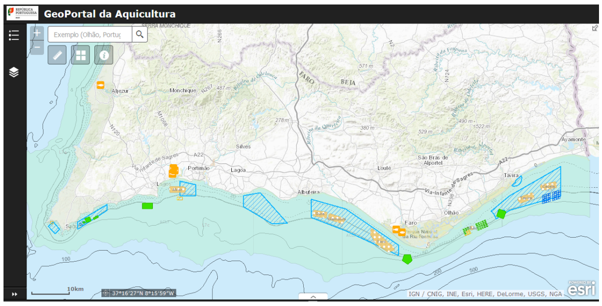

Figure 1: Image showing the location of areas available for offshore aquaculture in blue; offshore areas currently under use in green; offshore artificial reefs in brown and white; and fish ponds on land in brown and white (Source: www.eaquicultura.pt).

The satellite data were obtained from MERIS Level 2 Full Resolution (FR) and Reduced Resolution (RR) satellite images, with a spatial resolution of 290 m × 260 m and 1.2 km × 1.04 km, respectively. They were analysed, and API1 extracted, with the Basic ERS and ENVISAT (A) ATSR and MERIS Toolbox (BEAM version 4.9; www.brockmann-consult.de/cms/web/beam).

The results shows that MERIS API1 product decreased from inshore to offshore, with higher values occurring mainly between early spring and the end of the summer, and with lower values during winter. By using the satellite images for API1, it was possible to detect and track the development of algal blooms in coastal and marine waters (Fig. 2) that are food for shellfish but also have the potential to produce toxins from Harmful Algal Blooms. The study demonstrated the usefulness of remote sensing for supporting the aqua-

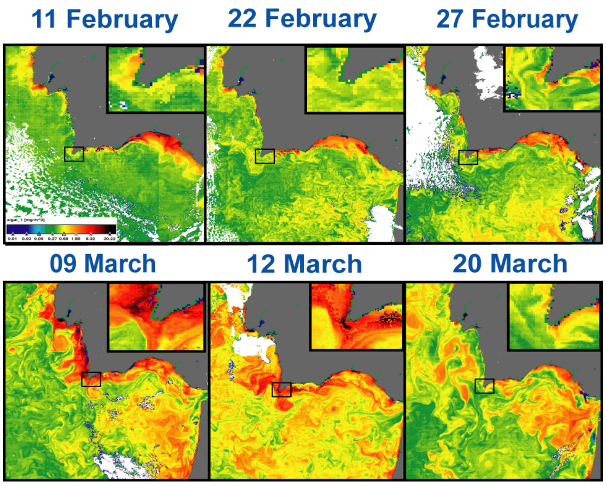

Figure 2: MERIS Reduced Resolution images of Algal Pigment Index 1 (API 1) showing the development of an algal bloom between February and March 2012 in the coastal waters of southern Portugal. Higher algal pigment concentrations shown in red. The inset zooms in on Cape St Vincent. Source: Christina et al. (2015).

culture economy that is developing in this study area and for the implementation of the MSFD and MSPFD.

7 Case Study: Adriatic

Valentini et al. (2016) created a map of the suitability of different parts of the northern Adriatic Sea for the farming of sea-bass and sea-bream. They used remote sensing, in-sea measurements, and models to provide information on the spatial distribution, and seasonal variation, of water characteristics important for fish-farming. The data obtained from satellite sensors were sea surface temperature (NASA MODIS and ESA Copernicus products) and chlorophyll and other OAC - from ESA MERIS).

The paper does not record the software used for the mapping, but the computational method seems to be that of a pixel-by-pixel binary analysis. For each pixel in the map, it was determined whether it showed space available for aquaculture or already assigned to another activity; whether the annual temperature range was suitable for fish growth; whether concentrations of OAC exceeded thresholds; whether water currents were above threshold values.[2]

The resulting map (Fig. 3) shows that the most suitable areas for fish farming were offshore and in the eastern part of the northern Adriatic. The western Adriatic was strongly influenced by the discharge of the Po river, with nutrients that stimulated phytoplankton growth and so resulted in chlorophyll concentrations above acceptable limits for sea-bass and sea-bream. These high concentrations, however, make the western Adriatic particular suitable for the cultivation of filter-feeding shellfish, as explored by Brigolin et al. (2017).

Brigolin et al. (2017) studied the potential area for aquaculture along the coast of the of the Emilia-Romagna Italian region (Northern Adriatic Sea) particularly for offshore shellfish culture of the Mediterranean mussel (*Mytilus galloprovincialis*). The study assessed: (i) if the establishment of new farms in deeper areas, beyond the 3 nautical miles would be beneficial for the activity, and if suitable to introduce new longline technology; (ii) the introduction of

[2] Unit 5, 'Introduction to AquaSpace integrating tools' explains pixel-based analysis in more detail.

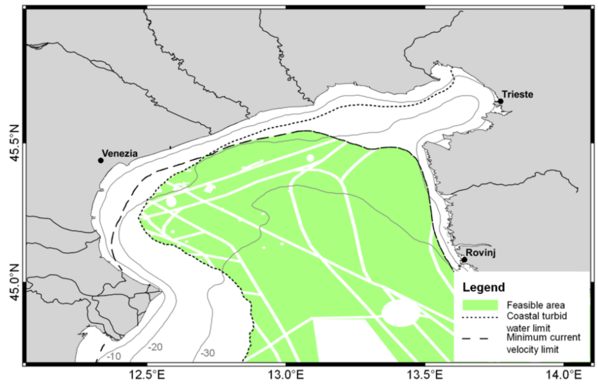

Figure 3: Feasibility analysis for fish aquaculture in northern Adriatic Sea. Green region is suitable and free of other activities. Source: Valentini et al. (2016).

a new species, such the Pacific oyster (*Crassostrea gigas*); and (iii) the risks for a farm because of storm events, particularly, in less sheltered off-shore areas.

Taking these three points into consideration, the methodology used to assess the suitability of the site for shellfish was the *Spatial Multi-Criteria Evaluation* (SMCE), which provided the framework to combine mathematical models and operational oceanography products. Intermediate level criteria (ILC) considered in the analysis included optimal growth conditions, environmental interactions, and socio-economic evaluation (Fig 4).[3]

Making use of resources provided by remote sensing and operational oceanography in site selection overcame the scarcity of data for model application. The use of environmental parameters provided by the remote sensing sensor MODIS (Moderate Resolution Imaging Spectroradiometer) between 2003-2012 (e.g. Sea Surface Temperature (SST) and concentration of Chlorophyll *a*) were used in the dynamic models of the present study. The non-linear effects of the different environmental parameters were integrated over the duration of the farming cycle.

The results of the SMCE showed that the whole coastal area between 0 and 3 nautical miles was highly suitable for farming of mussel, while the area comprised between 3 and 12 nautical miles was divided between the highly suitable northern part, and the less suitable southern part.

In addition, seven different scenarios of development of shellfish aquaculture industry were explored. The introduction of oyster farming did not change dramatically the degree of suitability for shellfish in the area. The results highlighted that: (i) the growth potential in this area was high; (ii) the space with suitability index > 0.5 increased when prioritizing the optimal growth condition criteria, and (iii) the socio-economic criterion was the most restrictive of the ILC.

The results from Brigolin et al. (2017) show that remote sensing can help identify zones for sustainable aquaculture in the Mediterranean Sea, where the space for these activities is becoming increasingly limited in coastal waters.

[3] The ‘BlueFarm’ tool developed and applied by Brigolin et al. is similar to the ‘AquaSpace Tool’ described by Gimpel et al. (2018) and introduced in unit 5.

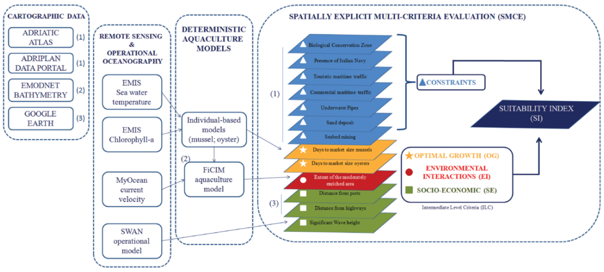

Figure 4: Information flow, and framework adopted in the SMCE. Colours mark the different Intermediate Level Criteria (ILC): (i) ‘optimal growth’ (orange); (ii) ‘environmental interactions’ (red); (iii) ‘socio economic evaluation’ (green). Constraints are shown in blue. Source: Brigolin et al. (2017).

8 Case Study: Mont St-Michel bay

Mont Saint-Michel Bay (North Brittany) was used as a case study by Thomas et al. (2011) to assess the potential of this marine ecosystem for shellfish aquaculture and to evaluate its carrying capacity. This study clarified the response of exploited species to environmental variations using robust eco-physiological models and available environmental data. It simulated the response of blue mussel (*Mytilus edulis* L.) to the spatio-temporal fluctuations of the environment in this study area by forcing a generic growth model based on Dynamic Energy Budgets (DEB) with satellite derived environmental data (i.e. temperature and food).

The sea-surface temperatures were taken from nightime infra-red emission measurements by the NOAA-18 satellite, and the chlorophyll concentrations were calculated using the OC4 algorithm from the ocean colour (sea-surface reflectance) measurements made by the NASA SeaWiFS.

The model was applied over nine years on a large area covering the entire bay and the simulations provided an evaluation of the spatio-temporal variability in mussel growth and showed the capacity of the DEB model to integrate satellite-derived data and to predict the variability of spatial and temporal growth of mussels. In addition, seasonal, inter-annual and spatial growth variations were also simulated. The results showed a strong link between food (satellite-estimated chlorophyll) and mussel growth.

9 Case Study: Nova Scotia

This case study concerns the use of low-altitude aerial photography from balloons and drones to visualise and map features in the vicinity of farms.

Delineation of marine habitat types and boundaries is essential to several management concerns facing aquaculture, mostly related to siting of farms. First, some habitats are specific to other activities such as fishery grounds, i.e. hard or vegetated bottom may be lobster habitat. Separation of aquaculture from these activities might lead to avoiding conflicts with other users. Second, some habitats may be sensitive (e.g. eelgrass beds) and avoided to minimize near-field influences such as ammonia streams from fish farms.

A challenge to resolution of these habitats is their coverage by water and therefore in-availability to many remote sensing techniques. Bathymetric lidar is an exception but this method is largely oriented only to quantifying depth. In contrast, ocean colour of the upper water column is a longstanding approach to quantities such as chlorophyll and turbidity, but these are temporally variable, and usually not indicative of benthic habitats. One solution to these issues arises via in-water remote sensing using echosounding. However, given the emphasis on airborne remote sensing in this report, we detail a study of intertidal habitats where the substrate is fully exposed to airborne imaging. The significance of this approach can be related most easily to intertidal bivalve culture, although the following example was not in an aquaculture area.

The conceptual basis for this research arises from landscape ecology (Zajac, 2008) wherein the size, patchiness, and arrangement of the landscape as a mosaic is quantified. Arising from terrestrial ecology, this approach is more developed where the landscapes are visible. In addition, faunal properties are associated with landscape structure, i.e. use of meadows and forest by bird species.

Fundamental to this discipline are landscape metrics that are derived with respect to single patch characteristics (e.g. area to perimeter ratio), components of the patch population (spatial distribution, connectivity), and landscape quantities (patch diversity, fragmentation). Although a detailed explanation of landscape statistics is beyond the scope of this summary, an excellent introductory text is Gergel and Turner (2017). Software used to calculate landscape indices includes freeware Fragstats (www.umass.edu/landeco/research/fragstats).

A feature present in shallow waters is marine vegetation, usually seaweeds or seagrasses. Fauna are often associated with vegetated bottoms, as nursery grounds or adult habitat, and seagrasses are known as sensitive habitat relative to ecosystem health. In the following example from Barrell and Grant (2015), we illustrate how remote sensing was able to detect intertidal features to map habitat. Fig. 5 shows the intersection of eelgrass (*Zostera marina*) and blue mussel (*Mytilus edulis*) beds in Halifax Harbour. We have emphasized marine plants, but bivalve reefs are significant biogenic features that provide a variety of ecosystem services. Remote sensing via a helium blimp was used to capture the images, but recent developments in drones have made this older technique less relevant for thus type of work. Image manipulation was used to highlight each habitat. It is obvious that the eelgrass grows as distinct features with repeating patterns. Other parts of the seagrass meadow are more continuous. The bivalve bed has more subtle patchiness. In this study, images captured at different times were used to describe changes in the eelgrass patches via landscape statistics.

The integration of landscape ecology into the FAO's Ecosystem Approach to Aquaculture is only in its initial stages, but continued applications in remote sensing will encourage progress. Consideration of the far field involves understanding the distribution of habitats and potential interaction with farm sites. A systematic approach for characterizing and describing habitats is necessary, and likely achieved through methodologies developed for landscape ecology. Remote sensing in underwater habitats remains an important component requiring further research.

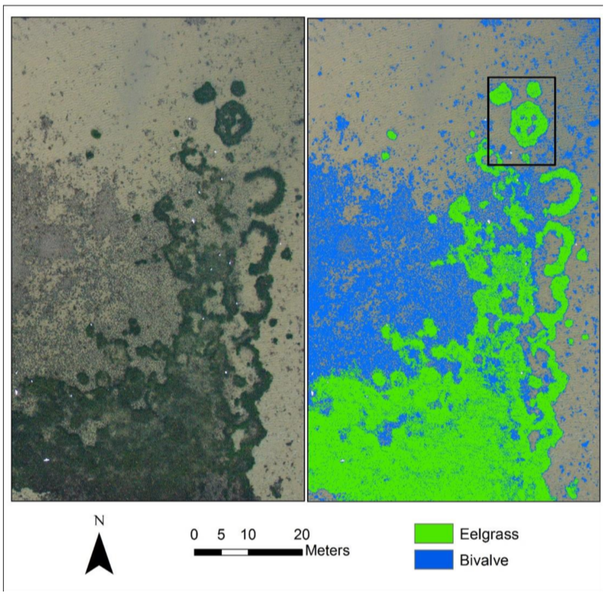

Figure 5: Aerial images of intertidal eelgrass and bivalve beds in Halifax Harbour. Source: Barrell and Grant (2015).

10 Exercises and SAQ

Exercise

The exercise involve the use of SNAP (Sentinel Application Platform) software to examine a Sentinel-3 image obtained from EUMETSAT. It is detailed in Appendix A.

Further reading

Study one of the papers associated with the Case Studies:

Algarve : Christina et al. (2015) (Open Access);

Adriatic : Valentini et al. (2016) or Brigolin et al. (2017) (both Open Access);

Mont St Michel : Thomas et al. (2011);

Nova Scotia : Barrell and Grant (2015).

Self Assessment Questions

The SAQs that follow test your achievement of the learning outcomes and help you think actively about the points raised in this lecture. No answers are given. The (parenthetical) numbers refer to sections and the letters to appendices.

1. What satellite data would help an aquacultural planner or developer to find a favourable environment for the cultivation of mussels? (7)

2. How are optical measurements made by a satellite converted to maps of chlorophyll concentration? (4)

3. What useful information was gained by using remote sensing to monitoring aquaculture concessions in the coastal waters of the Algarve coast and in the bays of Nova Scotia? (6, 9)

4. What were the contributions of remote sensing data to the case studies in the North Adriatic and Mont Saint-Michel bay? (7, 8)

5. Describe the main steps of the method for obtaining a processed image of Chlorophyll-a concentrations. (A)

Appendices

A Use of SNAP with Sentinel-3 data

SNAP is the ESA **Sentinel Application Platform** that provides analysis of the scientific data from the ERS-ENVISAT missions, the Sentinels 1/2/3 missions and a range of national and third party missions. Remotely sensed images are stored as arrays of data relating to pixels in maps. The exercise involves data that have already been subjected to some processing, to correct for atmospheric changes to the sea-leaving signal and to convert the latter into variables of interest, such as sea surface temperature (SST) or – in the present exercise – the phytoplankton photosynthetic pigment Chlorophyll *a* (Chl*a*). SNAP allows such data arrays to be explored and manipulated at different processing levels.

The exercise will have been completed when the student has obtained at least one chlorophyll image for a coastal region of their choice.

A.1 Install SNAP

Install the SNAP software from the ESA toolbox site at step.esa.int/main/toolboxes/snap, which provides guidance. Chose the 'Sentinel Toolboxes' and then follow the normal practice for your computer's OS to install the programme. Note where it was placed.[4]

[4] In the case of Mac OS X, it is most likely in `Applications/snap/bin`.

A.2 Get Sentinel-3 data

Although the SNAP app includes the ability to access ESA data as one of its functions, it is suggested, here, that the student visits the EUMETSAT site and downloads data independently of SNAP. In some cases this will require a user name and password.[5] A directory or folder should be set up to hold the (large) files before they are loaded into SNAP.

Tutorials are available from the SNAP website at step.esa.int/main/doc/tutorials. Or, go directly to YouTube for How to Visualise Sentinel 3 Data. As shown in this video,

- log in to the EUMETSAT site at coda.eumetsat.int/#/home;
- select region of interest on the map that is presented, and in the search criteria menu select `OL_2_WFR` from 'Product Type', `OLCI` from 'Instrument', and `L2` from 'Product Level', to get Sentinel-3 Level 2 Full Resolution water and atmosphere geophysical products from OLCI;
- you may be presented with many data sets, each from one pass of the satellite; identify the data set you want;
- download the data, which will be provided as a zip file: decompress it and store the resulting folder in the location you have identified for these data.

[5] In the case of EUMETSAT, a new user can set up an account when first visitng the web site.

A.3 Open data in SNAP

Sentinel-3 products are provided as a collection of files contained within a folder. The folder name is the actual product name, ending in `.SEN3`. Each folder contains a metadata file named `xfdumanifest.xml` and at least one *netcdf-file*. Each netcdf-file contains a subset of a Sentinel-3 product's content.

There are several ways to open a Sentinel-3 product within SNAP. Use this one:

- Choose `File` → `Open Product`,
- navigate to the `xfdumanifest.xml` file in your downloaded folder, and click Open;
- the name of the folder will appear in the `Product Explorer` window, with subfolders that include `Bands`;
- ctrl-click or right click on the folder name to bring up a menu;
- select Open RGB Image Window, accept Tristimulus profile, and click OK to bring up an image in SNAP's right-hand window.

The result may look different from that in the video; a cloud-covered image, for example, will be mainly white.[6] Continue as follows to output a chlorophyll image:

- in the `Product Explorer` window, → `Bands` → `CHL` → `CHL_OC4ME`
- ctrl-click or right click on the file name to bring up a menu;
- select Open Image Window to display the chlorophyll image;
- select (in main menus) `Layer` → `Layer Manager`;
- in the Layer Manager window select `Masks` → `WQSF_Isb_CLOUD`; close LM window;
- select (in main menus) `View` → `Tool Windows` → `Colour Manipulation`;
- In Colour window, select Table and click on colours to change the colour scale displayed for chlorophyll.

By this time, your SNAP screen should look something like Figure 6. The chorophyll image can be exported using the menu generated by ctrl-click or right click.

[6] If the image is cloud-covered, it will be desirable to return to EUMETSAT for another data set.

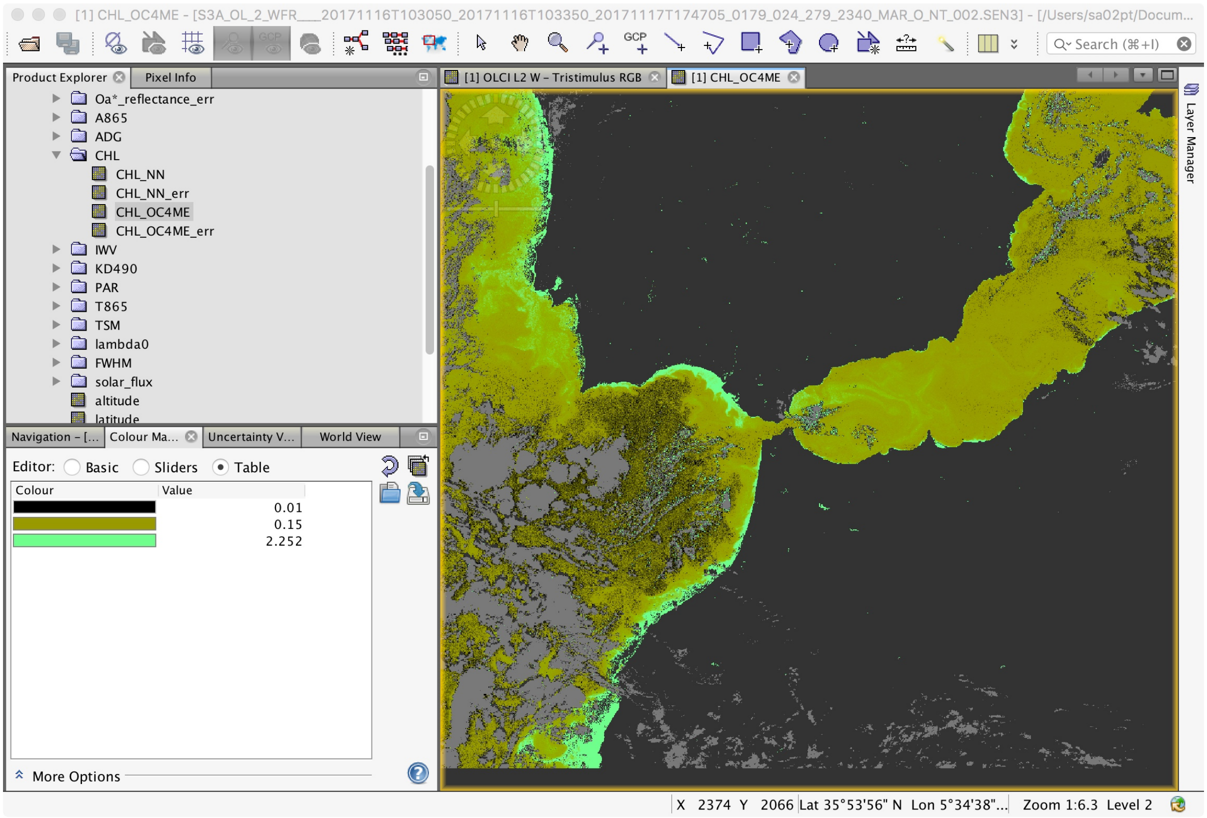

Figure 6: Screen grab from SNAP running under Mac OS X, showing an image centered on the Strait of Gibraltar on 16 November 2017

B NASA OceanColor site

The NASA OceanColor Web site provides access to NASA data from a variety of missions. If you use that link to enter the site's front page, chose `Data` → `Level 1 and 2 browsers`. Or follow the instructions below to see global maps of chlorophyll concentration or sea-surface temperature for a selected month and year, derived from MODIS.

- Go to NASA Ocean Color site page at oceancolor.gsfc.nasa.gov/cgi/browse.pl?sen=am
- set options to to **CHL**, MODIS aqua and day;
- select a month (in this case, August) and year (in this case, 2017), to display a global map for that month;
- set option to **SST** for a temperature map;
- if you want to do more, use the **help** for guidance.

This NASA web page also provides access to older data, including those from SeaWiFS (select MLAC) and CZCS.

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