Remote Sensing: Satellite and RPAS (Remotely Piloted Aircraft System)

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Abstract

Remote sensing is the science of detecting, monitoring, and acquiring information about the physical characteristics of a certain area without actually coming into contact with it, contrary to in situ observations. This chapter on satellites and RPASs (remotely piloted aircraft systems) provides an introduction to remote sensing, including a brief historical background; an overview of elements involved in remote sensing, for example, how radiation of different wavelengths reflected by or emitted from objects or materials in the distance is detected and measured; and the difference between spatial, temporal, and spectral ranges and resolutions. Advantages and limitations of remote sensing compared to in situ measurements are discussed as well as three main remote sensing platforms, i.e., ground level (towers and cranes), aerial (RPAS), and spaceborne (space shuttles, polar-orbiting satellites, and geostationary satellites), and their respective sensors, with a focus on satellite and RPAS sensors. The final two sections of the chapter

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take the reader from theory to practice, discussing the role that remote sensing plays in the development of many technologies and applications in major scientific fields, in particular, its application in marine analytical and environmental chemistry. The chapter concludes with a series of real-world practical case studies by authors of this chapter, in which different remote sensing techniques have been used around the world to monitor and assess areas of ecological concern, following extreme environmental events, such as volcanic eruptions, hurricanes, typhoons, phytoplankton blooms and catastrophic floods.

Keywords

Remote sensing · Satellite · RPAS · Environmental hazard

9.1 Introduction

Remote sensing is the science of detecting, monitoring, and acquiring information about the physical characteristics of a certain area without actually coming into contact with it, contrary to in situ or on-site observation. The process of remote sensing includes the detection and measurement of radiation of different wavelengths reflected by or emitted from objects or materials in the distance. These different wavelengths are key to their identification and form the basis for subsequent classification by class/type, substance, and spatial distribution.

By measuring the area's reflected and emitted radiation at a distance, typically from satellite, aircraft, or remotely piloted aircraft system (RPAS), special sensors can capture images of much larger areas than can be observed from the ground.

The term "remote sensing" was first used in the USA in the 1950s by Evelyn L. Pruitt, a research geographer at the US Office of Naval Research who, prompted by the need to define emerging imaging capabilities, came up with a dedicated term, which is now used ubiquitously. The concept of remote sensing itself, however, began much earlier with aerial photography as the first form of remotely capturing information about the Earth. Deriving from the Greek word photo, photography literally means light and graph, i.e., to draw. Going back to 500 BC, the philosopher Aristotle discovered that by directing sunlight through a pinhole, an upside-down image of the sun appeared on the ground. He used this method to view an eclipse without having to look directly at the sun.

After the French inventor Joseph Nicéphore Niépce successfully produced the first photographs in the 1800s, in 1850, Gaspard-Félix Tournachon ("Nadar") captured the first aerial photograph from a hot-air balloon of a French village in 1858, although his earliest surviving photograph was taken above Paris, France, in 1866. The oldest aerial photograph that has survived was taken in Boston, USA, in 1860 by James Wallace Black. In 1909, Wilbur Wright who, together with his brother Orville Wright—the famous Wright Brothers—developed the world's first airplane, was the first to successfully capture aerial images from an airplane. By World War I, airplanes equipped with cameras proved invaluable in military reconnaissance by providing aerial images of large surface areas, and by World War II, this became almost standard practice. In fact, the allied forces had a dedicated team of experts detecting hidden Nazi rocket bases with the help of millions of stereoscopic aerial images. During the Cold War between the Soviet Union and the USA, the Lockheed U-2 ("Dragon Lady") was able to fly at the ultrahigh altitude of 21,300 meters, resulting in an increased use of aerial reconnaissance. Shortly afterward in an attempt to conquer space, the Soviet Union launched Sputnik 1 and Sputnik 2, the first artificial satellites in space. The USA followed close behind with the successful launch of Explorer 1 in 1960, beginning the so-called Cold War Space Race.

These pioneers were followed by a long series of military and civilian space missions, and interest in using these platforms to obtain data from the Earth's atmosphere and surface soon became apparent. In 1960, the US National Aeronautics and Space Administration (NASA) launched the first meteorological satellite TIROS 1. The next in the series—TIROS 2—was the first to detect differences in sea-surface temperature, marking the beginning of ocean observation via satellite. Realizing this potential, NASA sponsored an initial meeting at the Woods Hole Oceanographic Institution (WHOI), in Falmouth, MA, in 1964 to discuss ways in which space-based remote sensing could contribute to oceanography, resulting in a road map of remote sensing toward ocean exploration.

The first Earth-observing satellite was launched in 1972, then known as the Earth Resources Technology Satellite (ERTS), and subsequently renamed Landsat 1, the first in a series of Landsat missions jointly managed by NASA and the U.S. Geological Survey (USGS), with the latest Landsat 9- in orbit since 2021. Landsat 1 was the first satellite launched with the specific aim to study and monitor Earth's landmasses. The Landsat program's continuous archive since 1972—the world's longest continuously acquired collection in fact—provides important land change data and current information that would otherwise not be available.

> I'd go to meetings and people were just jumping up and down because they had discovered another use for the data.
>
> Virginia T. Norwood, talking about early Landsat data, published in the article "The woman who brought us the world", MIT Technology Review, June 29, 2021
>
> That is one cool thing about Landsat... people are always finding new applications.
> Jeff Masek, Landsat 9 Project Scientist, NOVA Now podcast, Dec 17, 2020.

Remotely piloted aircraft systems (RPASs), also commonly referred to as unmanned aerial vehicles (UAVs), unmanned aircraft systems (UASs), and drones, are aircrafts that operate without any humans onboard, with the additional ground-based controller and a component that communicates with the RPAS. These systems are operated via remote control by a human operator, but there are also various degrees of autonomy, including autopilot assistance and even aircrafts that function completely autonomously without any human intervention. Although RPASs were originally developed for military purposes, in order to carry out missions that were too dangerous for human intervention, and continued doing so throughout the

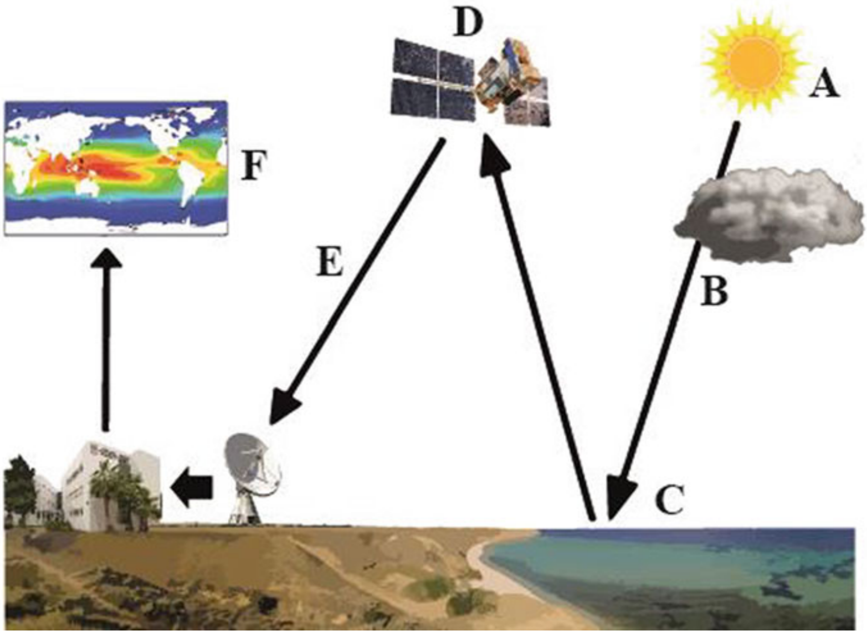


Fig. 9.1 Elements involved in remote sensing, mainly from satellite

twentieth century, the potential for their use in mapping was already appreciated in the late 1970s by different research groups (Przybilla and Wester-Ebbinghaus 1979; Wester-Ebbinghaus 1980). Navigation and mapping sensors were mounted onto radio-controlled platforms that could acquire low-altitude, high-resolution imagery, an idea that at first did not gain much attention in academia. However, in the technology and service industries, visionary companies as well as open-minded civil aviation authorities that anticipated the social and business benefits of unmanned aircrafts did start developing, applying, and regulating the technology (Petrie 2013).

The following elements of remote sensing are graphically presented in Fig. 9.1:

1. Illumination or source of energy (A). The basic requirement for remote sensing is a source of electromagnetic radiation that reaches the object or is directly emitted by the object itself.
2. Interaction between the radiation and the atmosphere (B). The electromagnetic radiation interacts with the atmosphere as it travels from the source to the object and from the object to the remote sensor. Therefore, the atmospheric interference contained in the signal that is received by the sensor must be eliminated.
3. Interaction with the object (C). In cases where the electromagnetic radiation comes from an external source and is not emitted by the object itself, it interacts with the object. This interaction depends on the properties of the land or ocean area and the electromagnetic radiation.

4. Detection of the electromagnetic radiation by the sensor (D). After emission from the object or reflection after interaction, the electromagnetic radiation is detected and registered by the sensor mounted on the remote sensing platform.
5. Transmission, reception, and processing (E). The signal registered by the sensor is transferred to a data reception station, stored in a specific format, and made available to end users. For RPASs, data are collected directly by the operator.
6. Interpretation and analysis (F). Using suitable processing methods, unwanted data are eliminated or corrected and made a parameter of interest.

9.2 Advantages and Limitations of Remote Sensing

In stark contrast to remote sensing, another way of obtaining information from the Earth is by means of field or in situ measurements, carried out with instruments in direct contact with the land or water. This intimate contact means that these measurements are usually more accurate than those made from space, which rarely match the former in precision. However, despite this, remotely sensed data have a number of advantages that compensate for this limitation. The first major advantage is related to the panoramic perspective and synoptic character of the data taken from space, as well as the possibility of obtaining information from remote or difficult to access areas, as is the case in some parts of the ocean, for example. The privileged position of remote sensors in space, hundreds of kilometers away from the Earth's surface, allows them to observe large areas, as opposed to the punctual measurements of in situ sampling. Moreover, this view of large portions of the Earth is almost instantaneous, contrasting with the long times needed for in situ sampling campaigns, especially larger areas or regions. In the specific case of the marine environment, its dynamic and changing nature, coupled with the characteristic scales of some oceanographic phenomena, gives remote sensing data a clear advantage when studying certain oceanographic phenomena. Moreover, certain aspects of the ocean, such as the ubiquity of mesoscale ocean eddies or the large extent of rapid phytoplankton blooms, were first revealed in space-based data. Another example in the marine environment concerns the global and repetitive coverage of the oceans. The orbits described by space platforms allow remote sensors to acquire data from almost the entire surface of the Earth in a continuous and repeatable manner. This global dimension is important as the ocean covers more than 70 % of the planet's surface, supports important ecosystems, and plays an important role in climate regulation. The repeatability of measurements allows multi-temporal studies to be carried out and the evolution of certain ocean processes to be monitored. Long-term time series of satellite data are now available, such as those obtained with the US National Oceanic and Atmospheric Administration's (NOAA) Geostationary Operational Environmental Satellites (GOES), which have been continuously collecting data since 1975. Another important advantage is the immediate data transmission from satellites to receiving stations and from there in near real-time to end users. This is possible thanks to the presentation of remotely sensed data in digital format, which also facilitates their visualization, interpretation, and integration with other data and models.

9.3 Spatial, Temporal, and Spectral Resolutions and Ranges

Generally speaking, resolution is defined as the ability of the sensor to discriminate detailed information about the object under study and is related to the smallest features or group of features that can be observed. The range, on the other hand, is analogous to the total coverage of the sensor and refers to the largest features or group of features that can be detected.

Spatial resolution refers to the size of the smallest portion of the land or ocean that the sensor is able to differentiate. In electro-optical sensors, it is often related to the concept of the instantaneous field of view (IFOV), which is the cone of angular visibility, measured in radians and observed at a given time by the sensor. It is precisely the intersection of the IFOV with the Earth's surface that determines the portion of the land or ocean that contributes to the measurement made by the sensor. The remote sensor detects the average electromagnetic radiation preceding this portion. It is usually assumed, but not always correct, that this resolution cell is square at least with regard to the nadir, and the side of the cell is taken as a measure of the spatial resolution. The smaller the size of this side, the better the spatial resolution of the data. This distance corresponds to the size of the smallest unit of information included in the satellite image, which is called a pixel (from *picture element*). When the sensor points the surface away from the nadir, the size of the resolution cell increases and becomes distorted, since the distance between the sensor and the object also increases, and effects of overlapping in the sampling of the land or sea surface and of the curvature of the Earth's surface that intensify these facts begin to be important. In any case, in electro-optical sensors, the spatial resolution mainly depends on the IFOV value and the orbital height, and to a lesser extent on other factors, such as the scanning speed and the number of detectors, whereas the spatial range is the total area covered by the remote sensor when acquiring the data. This range in electro-optical sensors is related to the concept of field of view (FOV), which is the total angle of view, measured in radians, observed by the sensor. The intersection of the FOV with the surface of the land or the ocean, which in turn depends on the orbital height, determines the spatial range, which is determined by the lateral extent of the observed surface, i.e., the swath. In general, resolution and spatial extent are inversely related, and each application requires remotely sensed data with a specific resolution and spatial extent.

Another important feature of satellite remote sensing acquisition systems is their ability to periodically observe the same area of the Earth's surface. This allows users to study dynamic processes and phenomena that occur near the land or sea surface. Therefore, *temporal resolution* refers to the periodicity (or frequency) with which the remote sensor can obtain data from the same area. The shorter this time period (or the higher the frequency), the better the temporal resolution of the sensor. This is also referred to as the revisit period of a satellite sensor and is usually several days, and the absolute temporal resolution of the remote sensing system to recapture images from the exact same area at the same viewing angle is equal to this revisit period.

While one of the strengths of remote sensing is the spatial detail and coverage of its measurements, the frequency with which these measurements are obtained is one of its weaknesses, especially when compared to in situ methods that allow data to be obtained almost continuously in time. The temporal resolution is primarily a function of the orbital characteristics of the platform, as well as the design of the sensor, especially its FOV, which determines the swath of land or ocean observed. Geostationary orbiting satellites that are directed toward the same region of the Earth's surface have the highest data acquisition frequency. In contrast, non-imaging sensors, such as the altimeter, which are located on polar-orbiting satellites, have the lowest temporal resolution. In these cases, the temporal resolution would be exactly the time it takes the satellite to complete a full orbital cycle, repeating the trace of its orbit over the Earth's surface. This orbital repeat cycle would be shortened to a duration of 1 to 3 days, albeit at the expense of very poor spatial coverage. If the orbital cycle is longer than 10 days, the spatial sampling density is greatly improved, but a temporal resolution longer than 10 days can be a significant disadvantage for many applications. Imaging remote sensors aboard polar-orbiting satellites can overcome problems associated with the orbital cycle depending on how large an area of the Earth's surface they observe as they travel.

The area of the electromagnetic spectrum in which the sensor operates should also be taken into account when considering temporal resolution. Sensors that detect visible radiation can only obtain data from the surface of the Earth during the day, while those that operate in the infrared can do so during both day and night, increasing their sampling frequency. Cloud coverage is an impediment to obtaining data for sensors that record visible and infrared radiation, affecting the temporal resolution in areas with frequent cloud cover. However, clouds are not an obstacle for sensors operating in the microwave region.

The temporal scale refers to the total period for which data from a certain region recorded by a sensor are available. This temporal range is limited in land and ocean observation from space by the lifetime of remote sensors and satellites, which is usually a few years. Once in orbit, it is not feasible to carry out direct repairs or maintenance of the satellite and its sensors, which deteriorate with the passage of time. Therefore, sometimes, in order to extend the time range, when a satellite is no longer operational, another satellite with similar characteristics is launched, increasing the time for which data are obtained with a sensor in a specific area. Through the previously mentioned Landsat series, for example, remote sensing data have been collected continuously this way since 1972. For aircraft or UAV, the temporal resolution is based on when flights are performed and accordingly scheduled by the pilot or the agency funding the flight.

Remote sensors do not detect electromagnetic radiation for an isolated wavelength but rather average radiation from continuous wavelength intervals centered on the wavelengths of interest. These ranges are referred to as spectral bands or sensor channels. The narrower the wavelength range for a particular band or channel, the finer the *spectral resolution*; thus, the spectral resolution refers to the sensor's ability to differentiate the electromagnetic radiation received in different wavelengths of the spectrum and depends on the spectral width of the sensor channels. The smaller the spectral width of these channels, the better the spectral resolution. Multispectral sensors record energy over several separate wavelength ranges at various spectral resolutions, and hyperspectral sensors, which are advanced multispectral sensors, detect hundreds of very narrow spectral bands throughout the visible, near-infrared, and mid-infrared portions of the electromagnetic spectrum. Their very high spectral resolution facilitates fine discrimination between different targets based on their spectral response in each of the narrow bands. Spectral range refers to the total number of spectral bands and the range of the electromagnetic spectrum covered by these bands. Therefore, the spectral range improves with increasing number of spectral bands and increasing size of inspected region. Radars are usually the acquisition systems with the lowest resolution and spectral range, many of which work with a single channel, although some of them are capable of distinguishing the polarization state of electromagnetic radiation. In contrast, electro-optical sensors have the highest number of narrow spectral bands that occupy a substantial region of the electromagnetic spectrum, in particular, hyperspectral systems, as is the case of the Hyperion sensor, which has 220 spectral bands. It can, therefore, be argued that the greater the number of bands in a sensor and the narrower the bands, the better the sensor's ability to reproduce the spectral response of an observed object. However, the choice of the number, width, and location of spectral bands included in a sensor is related to the objectives for which it is designed. Therefore, meteorological sensors such as Meteosat or AVHRR can operate correctly with only one band in the visible, since clouds do not offer significant chromatic variations. On the other hand, sensors designed to obtain information on ocean color, such as the SeaWiFS (Sea-viewing Wide Field-of-view Sensor) or MODIS, need several bands that allow them to distinguish different components that absorb and reflect light and estimate their concentration.

The different types of resolution and range described above/previously are not independent and are closely related to each other. As an obvious example, if the spatial resolution of a sensor is increased, then the spatial range decreases, and consequently, the temporal resolution also decreases. Similarly, by increasing the spatial resolution, the observation time and the amount of radiation arriving from the inspected area are reduced by decreasing the IFOV dimensions, and this can reduce the radiometric resolution and also the spectral resolution if the size of the sensor bands is increased to receive a greater amount of electromagnetic radiation.

Another important aspect to keep in mind is that any increase in resolution and/or range implies an increase in the volume of data to be processed. Therefore, it is not possible to increase all resolutions for a system simultaneously, and in designing a remote sensor, specific objectives should be the deciding factor for which resolutions and/or ranges should be improved.

9.4 Platforms

A platform is defined as the carrier for remote sensing sensors. There are three major remote sensing platforms: ground-level platforms (towers and cranes), aerial platforms (UAV, helicopters, and aircraft), and spaceborne platforms (space shuttles, polar-orbiting satellites, and geostationary satellites) (Fig 9.2). In this chapter, we focus on satellite and UAV sensors.

9.4.1 Satellite Agencies

9.4.1.1 National Aeronautics and Space Administration (NASA)

Established in 1958, NASA is the USA's civil space program. NASA studies the Earth, including climate, our sun, and our solar system, at its 20 centers and facilities located across the USA and in the only national laboratory in space.

Although satellite technology continues improving throughout the years, the mission stays the same: monitor Earth's land and coastal regions to help people manage natural resources.

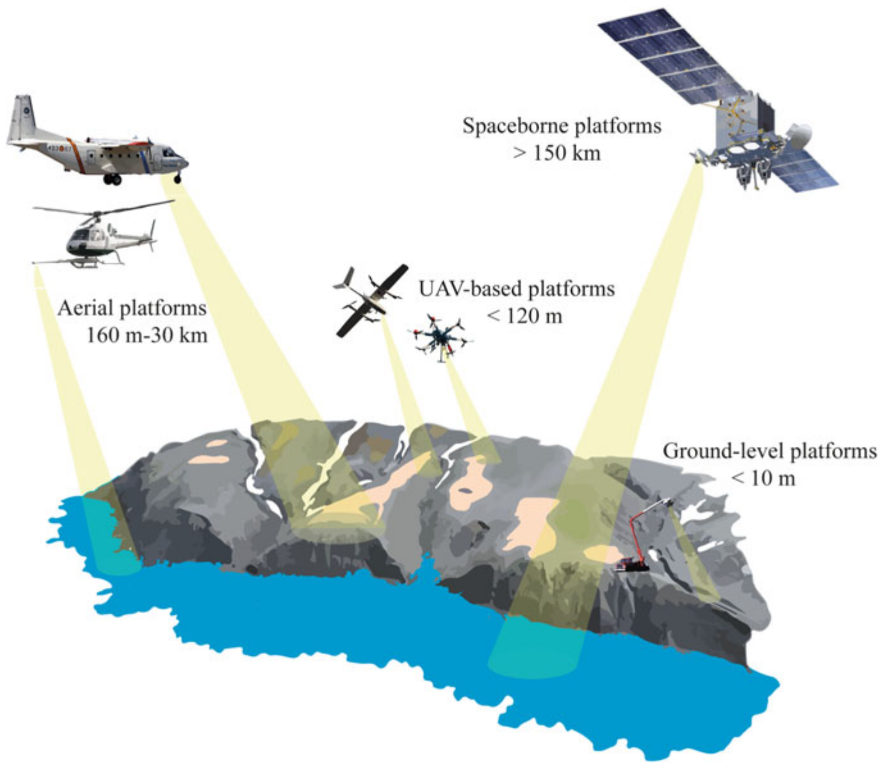


Fig. 9.2 Remote sensing platforms

NASA was responsible for the development and launch of a number of satellites with Earth applications, such as the Landsat series mentioned previously in the introduction. Landsat satellites give us a global perspective of how the Earth is changing because of natural causes, such as earthquakes, or because of human-caused drivers, such as greenhouse gas emissions that lead to warming temperatures on a global scale. The latest Landsat mission, Landsat 9, was launched on September 27, 2021, aboard a United Launch Alliance Atlas V rocket. Together in orbit, Landsat 9 and its sister satellite, Landsat 8, join forces to collect images from the planet with an 8-day revisit time. Although satellite technology continues improving throughout the years, the mission aims remain the same: monitor Earth's land and coastal regions to help people manage natural resources.

Additionally, MODIS (or Moderate Resolution Imaging Spectroradiometer) is a key instrument aboard the Terra and Aqua satellites launched by NASA. Terra MODIS and Aqua MODIS acquire multispectral data by viewing the entire Earth's surface on a daily basis. These data improve our understanding of global dynamics and processes that occur on land, in the oceans, and in the lower atmosphere, providing earth and climate measurements. MODIS plays a vital role in the development of validated, global, interactive Earth system models able to predict global change accurately enough to assist policymakers in making sound decisions concerning the protection of our environment.

9.4.1.2 National Oceanic and Atmospheric Administration (NOAA)

The NOAA Satellite and Information Service provides timely access to global environmental data from satellites and other sources to monitor the Earth. NOAA has a long history of geostationary and polar-orbiting environmental satellites in operational programs, such as the Joint Polar Satellite System (JPSS), the Geostationary Operational Environmental Satellite (GOES) program, and the Polar Operational Environmental Satellite (POES) program. The organization's satellite program has been essential for life-saving weather and climate forecasts for the USA and beyond. However, these satellites have also evolved to gather environmental data used for a wide range of applications in the ocean, coastal regions, agriculture, and the atmosphere, among many others, as well as in space. Geostationary satellites help monitor and predict weather and environmental events, including tropical systems, tornadoes, flash floods, dust storms, volcanic eruptions, and forest fires. Polar-orbiting satellites collect data for weather, climate, and environmental monitoring applications including precipitation, sea-surface temperatures, atmospheric temperature and humidity, sea ice extent, forest fires, volcanic eruptions, global vegetation analysis, as well as search and rescue. The Visible Infrared Imaging Radiometer Suite (VIIRS) instrument aboard the joint NASA/NOAA Suomi National Polar-orbiting Partnership (Suomi NPP) and NOAA-20 satellites produce reflectance imagery in near real-time (NRT), providing continuity from the MODIS corrected reflectance imagery that provides natural looking images. These continuous global environmental observations are subsequently derived to produce various geophysical variables that help to describe the Earth's oceanic, atmospheric, and terrestrial systems. NOAA's satellite data improve resilience to climate variability, maintain economic vitality, and improve the security and well-being of society.

9.4.1.3 The European Space Agency (ESA)

The ESA was founded in 1975 resulting from the merger of the European Launcher Development Organisation (ELDO) and the European Space Research Organisation (ESRO), both established in 1964. It is an international organization with 22 member states pushing the boundaries of science and technology and promoting economic growth in Europe. The ESA's mission is to shape the development of Europe's space capability and ensure that investment in space continues to deliver benefits to the citizens of Europe and the world. Therefore, it is dedicated to the peaceful exploration and the use of space for the benefit of humankind. By coordinating financial and intellectual resources of its members, it can undertake programs and activities far beyond the scope of any single European country. The ESA's programs are designed to discover and understand more about Earth, its immediate space environment, our solar system, and the universe, as well as to develop satellite-based technologies and services, and to promote European industries. The ESA also works closely with space organizations outside of Europe and has cooperated with NASA on many projects. The ESA also established a system of meteorological satellites known as Meteosat. The Medium Resolution Imaging Spectrometer (MERIS) was one of the main instruments on board the ESA's Envisat platform, a programmable spectrometer operating in the solar-reflective spectral range. Although it is primarily dedicated to ocean-color observations, MERIS broadened its scope of objectives to atmospheric and land surface-related studies, being operational throughout the Envisat mission lifetime, from 2002 to 2012. MERIS had a high spectral and radiometric resolution and a dual spatial resolution, within a global mission covering open ocean and coastal zone waters and a regional mission covering land surfaces. The primary objective of MERIS is to observe the color of the ocean, both in the open ocean (clear or case I waters) and in coastal zones (turbid or case II waters). These observations are used to derive estimates of the concentration of chlorophyll and sediments in suspension in the water, for example. It has also been used for monitoring and mapping *Posidonia oceanica* deposits. These measurements are useful for studying the oceanic component of the global carbon cycle and the productivity of these regions, among other applications.

Copernicus Program: "Europe's Eyes on Earth"

Copernicus is the European Union's Earth observation program, looking at the Earth and its environment to benefit all European citizens. It offers information services that draw from satellite Earth observation and in situ (non-space) data. The European Commission manages the program, and it is implemented in partnership with the member states, the ESA, the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT), the European Centre for Medium-Range Weather Forecasts (ECMWF), EU agencies, and Mercator Ocean. Global information from satellites and ground-based, airborne, and seaborne measurement systems provide information to help service providers, public authorities, and other international organizations improve European citizens' quality of life and beyond. The ESA is developing a series of next-generation Earth observation missions called Sentinels specifically for operational needs of the Copernicus program, on behalf of the joint ESA/European Commission initiative Copernicus. The objective of the Sentinel program is to replace retired Earth observation missions, such as the ERS and Envisat missions, or those that are currently nearing the end of their operational life span. This will ensure a continuity of data so that there are no gaps in ongoing studies. Each mission focuses on a different aspect of Earth observation; atmospheric, oceanic, and land monitoring and the data can be used in many applications. The information services provided are free and openly accessible to users, reaching different degrees of maturity. Some of the services were already declared operational several years ago: in 2012 for the Land Monitoring Service and the Emergency Management Service—Mapping—and in 2015 for the Atmosphere Monitoring Service and the Marine Environment Monitoring Service. Others were declared operational more recently: in 2016 for the Border Surveillance and Maritime Surveillance components of the security service and in May 2017 for the Support to External Action component and in July 2018 for the Climate Change Service.

Each Sentinel mission is based on a constellation of two satellites to fulfill revisit and coverage requirements, providing robust datasets for Copernicus services. The missions correspond to the following:

(a) *Sentinel-1* is a polar-orbiting, all-weather, day-and-night radar imaging mission for land and ocean services. With objectives of land and ocean monitoring, Sentinel-1 will be composed of two polar-orbiting satellites operating day and night and will perform radar imaging, enabling them to acquire imagery regardless of the weather. Sentinel-1A was launched on 3 April 2014 and Sentinel-1B on 25 April 2016.

(b) *Sentinel-2* is a polar-orbiting, multispectral high-resolution imaging mission. The objective of Sentinel-2 is land monitoring to provide, for example, imagery of vegetation, soil and water cover, inland waterways, and coastal areas. Sentinel-2 can also deliver information for emergency services. Sentinel-2A was launched on 23 June 2015, and Sentinel-2B followed on 7 March 2017.

(c) *Sentinel-3* is a multi-instrument mission, in which the primary objective is marine observation to measure sea-surface topography, sea- and land-surface temperature, ocean color, and land color with high-end accuracy and reliability. The mission supports ocean forecasting systems, as well as environmental and climate monitoring. Composed of three satellites, the mission's primary instrument is a radar altimeter, but polar-orbiting satellites will carry multiple instruments, including optical imagers. Sentinel-3A was launched on 16 February 2016, and Sentinel-3B joined its twin in orbit on 25 April 2018.

(d) *Sentinel-5* Precursor—also known as Sentinel-5P—is the forerunner of Sentinel-5 to provide timely data with high spatiotemporal resolution on a multitude of trace gases and aerosols affecting air quality, ozone, UV radiation, and climate. It has been developed to reduce data gaps between the Envisat satellite and the launch of Sentinel-5. Sentinel-5P was taken into orbit on 13 October 2017.

(e) *Sentinel-4* is a payload devoted to atmospheric monitoring that will be embarked upon a Meteosat Third Generation-Sounder (MTG-S) satellite in geostationary orbit. The mission aims to provide continuous monitoring of the composition of the Earth's atmosphere at high temporal and spatial resolution, and the data will be used to support monitoring and forecasting over Europe.

(f) *Sentinel-5* is a payload that will monitor the atmosphere from polar orbit aboard a MetOp Second Generation satellite.

(g) *Sentinel-6* Michael Freilich is the next radar altimetry reference mission to extend the legacy of sea-surface height measurements, until at least 2030. It is an Earth observation satellite mission developed to provide enhanced continuity to the very stable time series of mean sea-level measurements and ocean sea state that started in 1992, with the TOPEX/Poseidon mission. It carries a radar altimeter to measure global sea-surface height, primarily for operational oceanography and for climate studies. The first satellite was launched into orbit on 21 November 2020.

Did you know?

In 1972, Virginia Tower Norwood (also known as "the mother of Landsat") invented the first multispectral scanner to image Earth from space. Landsat 1 and its successors have been scanning the planet continuously ever since. Norwood was a pioneer inventor in the field of microwave antenna design. She designed the transmitter for a reconnaissance mission to the moon that cleared the way for the Apollo landings. And she conceived and led the development of the first multispectral scanner to image Earth from space—the first in a series of satellite-based scanners that have been continuously imaging the world for nearly half a century.

9.4.2 UAV

An unmanned aerial vehicle (UAV), also referred to as a "drone," is a relatively small and mobile flying robot that can operate autonomously or is controlled telemetrically over opened and confined areas, obtaining ultrahigh-resolution images at centimeter spatial resolution (Boukoberine et al. 2019; Hassanalian and Abdelkefi 2017; Townsend et al. 2020; Valavanis and Vachtsevanos 2015). The growing interest among the scientific community in the use of UAVs for research has led to the development of different types of drones in many shapes and sizes to be applied in a variety of activities. There are many metrics for UAV classification, such as size, mean takeoff weight (MTOW), operational altitude, or flight range (Valavanis and Vachtsevanos 2015; Watts et al. 2012). One of the most commonly accepted classifications is by wing type, and although multi-rotors are the most popular in the drone world, there are other options that work better in other applications. This section shows four categories of UAVs classified by wing type in single rotor, multi-rotor, fixed wing, and hybrid, each with their own characteristics (Table 9.1), and briefly described as follows.

Table 9.1 Advantages and disadvantages of different types of UAVs

UAV Type	Advantages	Disadvantages
Single rotor 	• VTOL and hover flight • Long endurance (higher if the drone is gas powered) • Greater area coverage • Higher payload capacity	• More dangerous and harder to fly • More expensive • Higher complexity
Multi-rotor 	• VTOL and hover flight • Easy control and maneuver • Very stable and good camera control • Accessibility (indoors and outdoors) • Simple design	• Short flight time • Limited area coverage • Small payload capabilities
Fixed wing 	• Long-endurance flight • Greater area coverage • Fast flight speed • Heavier payload capacity • Higher flight altitude and flight time	• Space is necessary for launching and recovery • No VTOL and hover flight • Harder to fly • Only forward movement • More expensive
Hybrid 	• VTOL flight • Long-endurance flight • Large area coverage	• Under development • Not perfect transition between hovering and forward flight

9.4.2.1 Single Rotor

This platform consists of a single main rotor and a tail rotor for flight heading. It is commonly used in manned aviation, whereas single rotor drones are not commonly used for research purposes by the scientific community. Its main feature is greater endurance compared to multi-rotors (which can be even higher with gas engines), which also allows it to cover large areas. Its main advantages are its high load capacity (being able to equip, e.g., an aerial lidar device) and the ability to combine hovering with fast-forward flights. Its drawbacks are its complexity, cost, danger, and flight difficulty.

9.4.2.2 Multi-rotor

This type of UAV, the most commonly used in scientific research, consists of multiple rotors; therefore, it is classified according to the number of rotor blades. These devices are easily controllable and highly maneuverable and can monitor hard-to-reach places indoors and outdoors. However, they are very limited by the flight time since batteries have little autonomy and by the payload capacity, which is very reduced compared to other types of UAVs. In addition, these drawbacks limit the spatial coverage of these devices, requiring more than one maneuver to cover a wide flight area.

9.4.2.3 Fixed Wing

These drones use a single wing for their lift instead of vertical lift rotors, which makes them more efficient. The fact that they only have to use energy for moving, and not for staying in the air, allows them to cover much greater distances and to have a longer flight time (which can be even higher with gas engines). However, their main disadvantage lies in the difficulty of working in geographically limited areas, since they require space for takeoff and landing maneuvers. In addition, they are expensive and difficult to handle and can only fly forward, which rules out the vast majority of photogrammetric work.

9.4.2.4 Hybrid

This platform merges benefits of fixed-wing and multi-rotor drones, thus assuming a transition between two modes during flight. This means greater flight autonomy and, therefore, greater area coverage, which makes it the ideal platform for scientific research in almost any location. However, despite its many advantages, this device is still under development, especially in terms of optimization of transition between flight modes.

9.5 Types of Sensors

As described previously, remote sensing sensors receive electromagnetic radiation and convert it into a signal that can be recorded and displayed as either numerical data or images. Imaging sensors are the core component of any remote sensing system, and they come with a wide range of spatial, temporal, and spectral resolutions. Sensor system implementation is equally varied, including single- and multiple-sensor configurations, active and passive sensors, and completely solid or optomechanical sensors. In general, sensors are commonly grouped by their spectral sensitivity, and there are several regions of the electromagnetic spectrum that are

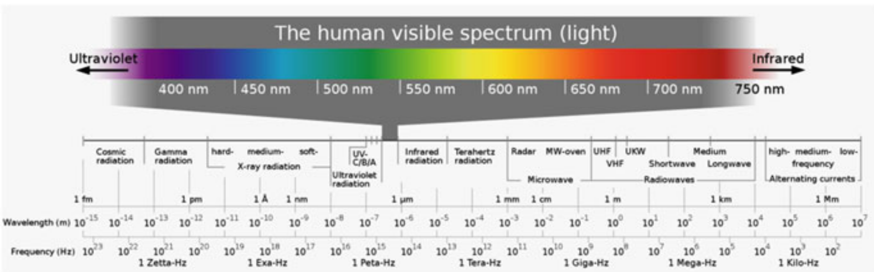


Fig. 9.3 Electromagnetic spectrum

useful for remote sensing. Figure 9.3 shows the electromagnetic spectrum with the most important bands used in remote sensing.

9.5.1 Satellite Sensors

As briefly mentioned in the introduction, remote sensing instruments can be either active or passive. While active instruments have their own illumination or source of energy, passive instruments detect natural energy that is reflected off of or emitted directly by the observed target, with reflected sunlight being the most common external source of radiation sensed by passive instruments (optical sensors). These sensors work in several bands including spectra within and beyond what humans can see (visible, IR, NIR, TIR, and microwave).

Optical remote sensing is a passive technique for land and ocean observation that relies on the sun as a source of illumination. These systems are classified into different types according to the number of spectral bands used in image acquisition: panchromatic sensor (1 single band that combines Red, Green, and Blue bands), multispectral imaging sensors (3–50 spectral bands), and hyperspectral imaging sensors (50–300 spectral bands). These sensors use the following types of technologies: (a) multispectral imaging using discrete detectors and scanning mirrors (e.g., Landsat multispectral scanner and Landsat thematic mapper), (b) multispectral imaging using linear arrays (e.g., SPOT and IKONOS), and (c) imaging spectrometry using linear and area arrays (e.g., AVIRIS and MODIS). Optical sensor data enable the assessment of sea-surface properties, such as phytoplankton concentration, chromophoric dissolved organic matter (CDOM), suspended matter (SPM), type of benthic substrate, vegetation composition, and bathymetry in shallow waters.

Active instruments, which have their own source of energy (electromagnetic radiation) to illuminate the target object, send a pulse of energy from the sensor to the object and subsequently receive the radiation that is reflected back from the target object. There are many different types of active remote sensors, including the following examples:

Radars (radio detection and ranging) use a transmitter operating at either radio or microwave frequencies to emit electromagnetic radiation, and a directional antenna or receiver to measure the time of arrival of reflected or backscattered pulses of radiation from target objects. Distance to the object is determined since electromagnetic radiation propagates at the speed of light. These sensors are widely used for monitoring oil spills.

Scatterometers are a type of active high-frequency microwave radars that transmit microwave pulses to the Earth’s surface and subsequently measure the radiation that is backscattered to the instrument. These backscattered coefficients are related to surface roughness. Over ocean surfaces, measurements of backscattered radiation in the microwave spectral region can be used to derive maps of surface wind speed and direction.

Lidar (light detection and ranging) is a remote sensing method that uses light in the form of a pulsed laser to measure variable distances to the Earth. These light pulses—combined with other data recorded by the airborne system—generate precise, three-dimensional information about the shape of the Earth and its surface characteristics.

A lidar instrument primarily comprises a laser, a scanner, and a specialized GPS receiver. Airplanes and helicopters are the most commonly used platforms for acquiring lidar data over broad areas, with two main types of lidar being topographic and bathymetric. Topographic lidar typically uses a near-infrared laser to map the land, while bathymetric lidar uses water-penetrating green light to also measure seafloor and riverbed elevations. Distance to the target object is determined by recording the time between transmitted and backscattered pulses and using the speed of light to calculate the distance traveled.

9.5.2 UAV Sensors

Unmanned aerial vehicles (UAVs) can be equipped with a wide range of sensors, ranging from the visible to the infrared spectrum (Fig. 9.3), and are in continuous technological evolution in order to guarantee the success of marine and coastal monitoring missions. Most of the existing satellite or aircraft sensors have been adapted to the size and load capacity of UAV platforms, resulting in a wide variety of low-cost models of RGB, multispectral, hyperspectral, thermal, and lidar cameras (Ren et al. 2019; Valavanis and Vachtsevanos 2015). The discussed sensors and their characteristics as well as some case studies are summarized in Table 9.2, and details of these sensors are highlighted in the following subsections.

RGB sensor. This is the most common type of sensor mounted on a UAV platform and allows images of true color of red, green, and blue bands from the visible spectrum (between 400 and 760 nm) to be acquired. High-quality RGB cameras ensure quality photogrammetric products and low-signal/noise-ratio data for data analysis (Ren et al. 2019; Valavanis and Vachtsevanos 2015). The vast majority of drones used for entertainment or television are manufactured with their own integrated RGB sensor (e.g., DJI drones). However, in scientific research, mountable RGB sensors are more commonly used (e.g., Sony Nex5n RGB, Zenmuse Z30, and Sony A6000), since they offer the option of parameter modification, such as focal length, lens distortion, or pixel size, and are successfully used to monitor coastal environmental issues, such as plastics/debris accumulation (Garcia-Garin et al. 2020), invasive species proliferation (Marzialetti et al. 2021), or harmful algal blooms (HABs, Xu et al. 2018).

Thermal sensor. Lightweight thermal sensors that can acquire information in the mid- and long-wave infrared (wavelengths from 5000 nm to 35,000 nm) are broadly used in surface temperature and thermal emission measurements. Unlike satellite imagery, atmospheric effects are negligible, the data processing is less complex, and temperature values are theoretically more precise. However, the lower structural complexity of UAV platforms means that lightweight thermal sensors generally do not come with cooled detectors, thus resulting in lower capture rates, lower spatial resolution, and lower sensitivity due to a reduced signal-to-noise ratio (Valavanis

Table 9.2 Most commonly used UAV sensor types with examples

Sensor Type		Electromagnetic Spectrum	Examples	Case Studies
RGB		Visible light	Sony Nex5n RGB, Zenmuse Z30, Sony A6000, and Yuneec E90	Plastic/Debris Detection (Garcia-Garin et al. 2020), Invasive Species Detection (Marzialetti et al. 2021), and HABs monitoring (Xu et al. 2018)
Thermal		Mid-wave infrared and long-wave infrared	FLIR Vue Pro 19 mm and Workswell Wiris Pro	Plastic/Debris Detection (Goddijn-Murphy and Williamson 2019, Topouzelis et al. 2019) and HAB monitoring (Berni et al. 2009)
Multispectral		Visible light and near infrared	MicaSense RedEdge-MX, MicaSense RedEdge-P, and Sentera 6X	Plastic/Debris Detection (Biermann et al. 2020), Invasive Species Detection (Marzialetti et al. 2021), and HAB monitoring (Goldberg et al. 2016)
Hyperspectral		Visible light, near infrared, and short-wave infrared	HySpex SWIR-640 and Headwall VNIR-SWIR	Plastic/Debris Detection (Balsi et al. 2021), Invasive Species Detection (Bolch et al. 2021), and HAB monitoring (Young et al. 2019)
Lidar		Visible light and infrared	LeddarTech Vu8, LeddarOne and LiDAR's Puck Lite	Plastic/Debris Detection (Ge et al. 2016)

and Vachtsevanos 2015). Some typical thermal camera models equipped on drones (e.g., FLIR Vue Pro 19 mm and Workswell Wiris Pro) have been successfully used for the detection of macroplastics in coastal areas (Goddijn-Murphy and Williamson 2019; Topouzelis et al. 2019) or for the monitoring of HABs (Berni et al. 2009), among others.

Multispectral sensor. This sensor can collect spectral information in more than two channels, in addition to standard RGB bands. Its small size and low price, in addition to the high precision in the medium-scale monitoring of the surface, make it a fundamental device for scientific research (Ren et al. 2019). Multispectral cameras are usually employed in precision agriculture, although they are increasingly used to monitor marine/coastal environmental phenomena, such as detection and identification of marine litter (Biermann et al. 2020), detection of invasive species (Marzialetti et al. 2021), or monitoring of HABs (Goldberg et al. 2016). Examples include the MicaSense RedEdge-MX, the MicaSense RedEdge-P, the Sentera 6X, or the Parrot Sequoia.

Hyperspectral sensor. Compared with the limited number of bands that multispectral sensors have, hyperspectral sensors acquire spectral information in greater abundance (hundreds of narrow bands) and higher resolution. In addition, the vast majority are linear-array cameras, which capture large volumes of extremely useful information to address coastal events such as the spectral identification of marine litter (Balsi et al. 2021) or the monitoring of the proliferation of invasive species based on the enhanced spectral detectability (Bolch et al. 2021). However, these sensors are less accessible due to their high cost and because they have compatibility limitations with drones, since they require a large payload capacity to equip them. Storage is another limiting factor given the multidimensional nature of hyperspectral datasets (Ren et al. 2019; Valavanis and Vachtsevanos 2015). Some of the most used models are the HySpex SWIR-640 sensor or the VNIR-SWIR Headwall sensor.

Lidar sensor. As described in the previous section on satellite sensors, lidar sensors work with a laser that is transmitted to the ground surface and subsequently received by the sensor after surface reflection, operating as a radar and assuming one of the most precise ways to obtain real-time geometric data. These sensors allow information to be obtained in places where there are not enough ground control points (GCPs), and they also allow the generation of precise 3D models of surface information. Although they require higher payloads to be mounted on UAVs, they are increasingly used in marine research due to their relative low cost and the precision of the data obtained (Ren et al. 2019; Valavanis and Vachtsevanos 2015). Some examples of lidar sensors that have been equipped on drones are LeddarTech Vu8, LeddarOne, or LiDAR's Puck Lite, which have allowed, among other applications, the detection and identification of macroplastics in coastal regions (Ge et al. 2016).

9.6 Application in Marine Analytical and Environmental Chemistry

Remote sensing plays a huge role in the development of many technologies and applications in major scientific fields, being one of the most innovative research areas for Earth observation. Remote sensing presents a cost-effective complementary approach for a comprehensive assessment of marine environments and aquatic resources, providing several advantages compared to traditional in situ approaches. Remote sensing observations are useful in obtaining up-to-date water quality patterns, biogeochemical parameters, and indicators of environmental health of large areas at any given time and also monitor their dynamic patterns of change, especially in ocean observation. Remote sensing imagery can be used to study degradation of inland and marine environments, pollution, and eutrophication of water bodies. In addition, remote sensing is extensively used to track and monitor the impact of natural hazards, such as hurricanes, floods, active volcanoes, and typhoons on coastal regions in order to detect possible damage and plan appropriate response and management, preventing damage as far as possible. These events have profound effects on marine life and the surrounding environment, requiring a prompt response in order to avoid negative impacts. Some unique remote sensing technologies are also applied for mapping out underwater reefs and bathymetry in strategic locations. Moreover, satellite information is helpful for monitoring and identifying algae with the rapid preparation of synoptic maps. A lot can be learned about a marine ecosystem's health by studying algae or harmful algal blooms (HABs), since they are an indicator of the amount of nitrogen and phosphorous that is leaking into a certain water body. Through long-term monitoring, biochemical seawater properties can be understood, supporting the evaluation of environmental problems and potential health risks and preventing negative impacts on the environment and biodiversity. Therefore, remote sensing provides real-time and historical data for studies of water quality trends and potential impacts of land use and land cover change on biogeochemical parameters over coastal and marine ecosystems. This added-value information is used by regional planners and administrators to conserve and frame policy matters for sustainable development at local, regional, and national scales in the context of a changing global climate.

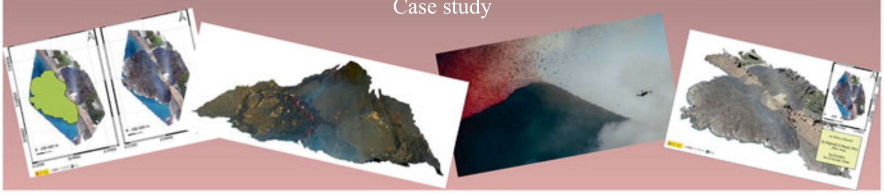
9.7 Case Studies

A series of case studies are presented as follows, in which different remote sensing techniques are used with different sensors in the context of marine analytical and environmental chemistry:

9.7.1. Volcanic eruption in La Palma, Spain
9.7.2. Monitoring marine macrophytes, Spain
9.7.3. Antarctic environmental research
9.7.4. Impact of a hurricane in the USA
9.7.5. Phytoplankton blooms in Chile
9.7.6. Impact of typhoons in the Philippines
9.7.7. Dredging operations in an estuary in Spain
9.7.8. Catastrophic floods in Spain

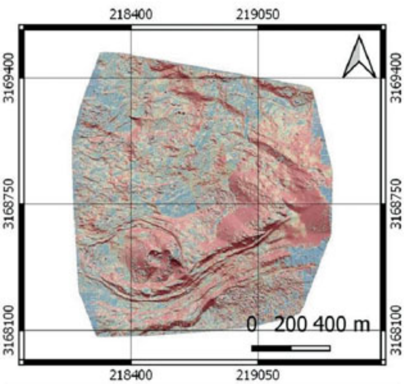
Volcanic eruption in La Palma

Case study



In September 19th 2021, the Cumbre Vieja volcanic eruption took place on La Palma Island, Spain. The lava flow and the material expelled by the volcano did not only affect human infrastructure and the general economy of the island, but also reached the ocean near the municipality of Tazacorte forming a lava delta on the west cliff of the island, with significant physical-chemical and biological alterations of seawater. This study highlights the value of Unmanned Aerial Vehicles (UAVs) as a feasible, precise, rapid and safe tool for real time monitoring of the impacts of a volcanic event. In addition, UAVs substantially contributed helping scientists and managers in the emergency assessment. Different areas affected by the volcanic eruption were assessed with optical RGB, thermal and multispectral sensors, and a water sampling device, equipped on board drones.

More info: *Román et al. (2021). Unmanned aerial vehicles (UAVs) as a tool for hazard assessment: The 2021 eruption of Cumbre Vieja volcano, La Palma Island (Spain). Science of the Total Environment, 843: 157092.*



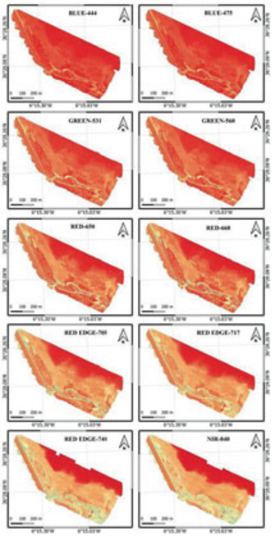
Slope map generated with the SfM workflow followed for the DJI Mavic 2 Pro flight performed on October 2021 over the volcanic crater.

Acknowledgements*: This work was financially supported by funds from the Interdisciplinary Thematic Platforms (PTI) WATER:iOS and TELEDETECT granted by the Spanish National Research Council (CSIC) and the grants/projects EQC2018-004275-P, EQC2019-005721, RTI2018-098784-J-I00 and IJC2019-039382-I funded by MCIN/AEI/10.13039/501100011033 and by "ERDF A way of making Europe". Data at sea were collected in the context of the VULCANA-III (IEO-2021-2023) project funded by the IEO-CSIC.*

Monitoring Marine Macrophytes

Case study

Marine macrophytes constitute one of the most productive ecosystems on the planet due to the large amount of ecosystem services they provide, since they act as atmospheric CO_2 sinks, provide refuge and food for numerous animal species or perform coastal protection tasks, among others. However, they are seriously affected by climate change and anthropogenic activities, and that is why their monitoring is essential and has evolved over the years until the development of a methodology based on the use of sensors embedded in UAVs, which make it possible to accurately identify the different species and to quantify the extent of these meadows in coastal areas. In this study, a 10-band multispectral sensor (MicaSense RedEdge-MX) is used on a hexacopter drone for the detection and subsequent supervised classification of marine macrophyte meadows in Santibañez (Cádiz Bay, Spain). The results obtained confirm the suitability of this technique to study and monitor marine macrophytes in a range between 0-2 meters depth in coastal areas.



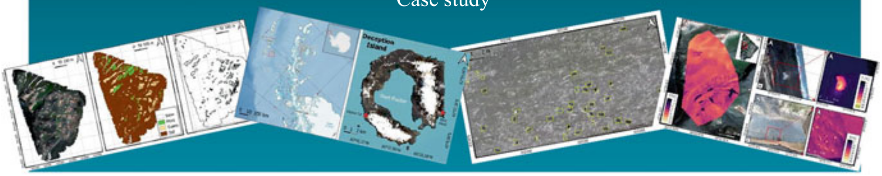
At-sensor reflectance orthomosaics of multispectral bands in the study area.

More info: *Román et al. (2021). Using a UAV-Mounted Multispectral Camera for the Monitoring of Marine Macrophytes. Frontiers in Marine Science, 8: 722698.*

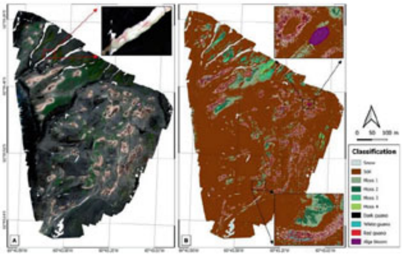
Acknowledgements*: This research was supported by the project EQC2018-004175- and PY20_00244 funded by the National Government and Regional Government of Andalusia, respectively.*

Antarctic Environmental Research

Case study



The importance of the Antarctic continent in the Earth's climate, in global ocean circulation and in the global ecosystem is well known. That is why, given the impact of climate change on the polar regions, the need arises among the scientific community to know the functioning and the different responses of the Antarctic ecosystem to extreme environmental conditions, seasonality and isolation. This study presents a novel, fast and accurate methodology based on the use of Unmanned Aerial Vehicles (UAVs) to achieve a comprehensive understanding of the processes taken place in Antarctica, using Deception Island (South Shetland Islands) as a case study. UAV surveys with visible, thermal and multispectral sensors, and a water sampling device, allow the elaboration of precise thematic ecological maps, 3D models of geological structures, anomalous thermal zones mapping, or the sample of dissolved chemicals waters from inaccessible areas.

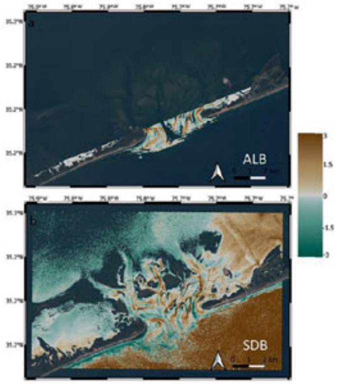


Photomosaics of Vapour Col Chinstrap penguin colony on Deception Island composed of 3800 pictures taken at 100 m altitude with a 10 bands multispectral camera onboard a hexacopter, achieving 6 cm/pixel size. Panel (A): visible RGB mosaic (Red-668, Green-560 and Blue-475) with a zoom capture showing red snow patch; Panel (B): thematic map generated through non-supervised classification method.

More info: *Tovar-Sánchez et al. (2021). Applications of unmanned aerial vehicles in Antarctic environmental research. Scientific Reports, 11: 21717.*

Acknowledgements*: This research has been funded by the Spanish Government projects PiMetAn (ref. RTI2018-098048-BI00), EQC2018-004275-P and EQC2019-005721. This research is part of the POLARCSIC research initiatives.*

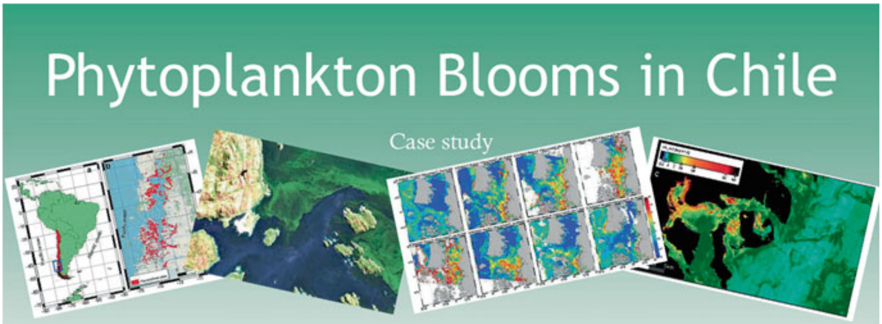
Mapping bathymetric change is a core task for a wide range of navigation, research, monitoring, and design applications. Satellite-derived bathymetry (SDB) can support this activity, particularly when using data from a platform, like the Sentinel-2A/B twin mission of the Copernicus programme, which provides routine and repetitive image acquisition at 10 m spatial resolution. In this study, we use SDB, in comparison with high-resolution airborne lidar bathymetry (ALB), to quantify bathymetric changes at two inlets in North Carolina following the impacts of the devastating Hurricane Florence in September 2018. We identify bathymetric changes in shallow areas with navigation channels in two of the most dynamic inlets in the Outer Banks, Oregon and Hatteras. Multiple lidar surveys are used to validate the SDB method and for an assessment of accuracy and vertical uncertainty. The multi-temporal SDB products and ALB both show similar results in the erosion/accretion patterns. Comparing the change determined from the two methods, gives a median absolute error of ~0.5 m of SDB compared with ALB, with bias of ±0.2 m for depths ≤7 m; errors that are equivalent to those associated with the SDB estimated absolute depths. By implementing the multi-temporal turbidity correction, SDB based on Sentinel-2 may substantially enhance existing survey methods for change detection and support operational and recursive coastal monitoring on local to regional scales.



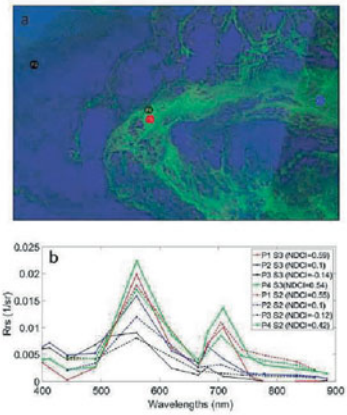
a) Erosion/deposition map after Hurricane Florence in Hatteras Inlet for high-resolution lidar surveys (ALB 2017-ALB 2019), and for b) SDB (SDB 2017-SDB 2019). Green colors indicate erosion (deepening) and brown colors accretion (shallowing). The base map corresponds to a Sentinel-2 image at 10 m spatial resolution.

More information: *Caballero, I., & Stumpf, R. P. (2021). On the use of Sentinel-2 satellites and lidar surveys for the change detection of shallow bathymetry: The case study of North Carolina inlets. Coastal Engineering, 103936.*

Acknowledgements*: This research was supported by the Spanish Ministry of Science, Innovation and Universities (MCIU), the Spanish State Research Agency (AEI) and the European Regional Development Fund (ERDF) (Sen2Coast Project; RTI2018-098784-J-I00). The research was also supported by the National Oceanic and Atmospheric Administration (NOAA).*



During the southern summer of 2020, large phytoplankton blooms were detected using satellite technology in Chile (western Patagonia), where intensive salmonid aquaculture is carried out. Some harvesting sites recorded massive fish mortalities, which were associated with the presence of the dinoflagellate species *Cochlodinium sp*. The bloom included other phytoplankton species, such as *Lepidodinium chlorophorum*, which persistently changed the colour of the ocean to green. These blooms coincided with the government-managed emergency lockdown due to the COVID-19 pandemic. Local in situ sampling was reduced. However, imagery from the Copernicus programme allowed operational monitoring. This study shows the benefits of both Sentinel-3 and Sentinel-2 satellites in terms of their spectral, spatial and temporal capabilities for improved algal bloom monitoring. These novel tools, which can foster optimal decision-making, are available for delivering early warning during natural catastrophes and blockages, such as those that occurred during the global COVID-19 lockdown.



a) RGB (red-green-blue) composite from a Sentinel-3 scene acquired on 8 April 2020, b) Spectral signature in some pixels (P1, P2, P3, and P4) of the scene from Sentinel-3 (300m) and Sentinel-2 on 8 April 2020. The normalized difference chlorophyll index (NDCI) values are indicated for each pixel and satellite (Sentinel-3 and Sentinel-2).

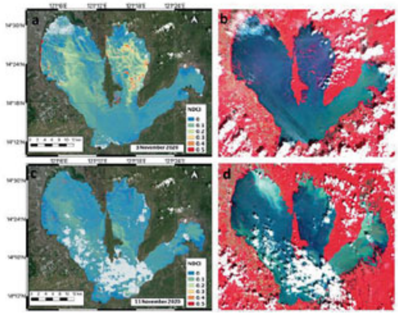
More information: *Rodríguez-Benito et al. (2020). Using Copernicus Sentinel-2 and Sentinel-3 data to monitor harmful algal blooms in Southern Chile during the COVID-19 lockdown. Marine Pollution Bulletin, 161, 111722.*

Acknowledgements*: This research was supported by Mariscope companies, the Spanish Ministry of Science, Innovation and Universities (MCIU), the Spanish State Research Agency (AEI) and the European Regional Development Fund (ERDF) in the frame of the Sen2Coast Project (RTI2018-098784-J-I00).*

Impact of typhoons in Philippines

Case study

Laguna Lake, the largest freshwater lake in the Philippines, is permanently subject to nutrient-driven eutrophication and pollution and experiences harmful algal blooms (cyanoHABs) periodically with serious socio-economic implications. The aim of this study is to evaluate the suitability of the Sentinel-2 imagery of the European Commission's Copernicus Earth Observation programme for lake monitoring during the 2020 Pacific typhoon season (September-November 2020). The Case-2 Regional CoastColour processor is used to atmospherically correct Level 1 data and generate water quality parameters, such as chlorophyll-a (Chl-a) and total suspended matter (TSM) at 10 m. Results show that Super Typhoon Goni and Typhoon Vamco delivered high suspended sediment loads to the reservoir at concentrations above 170 g/m^3 compared to pre-storm situations (0-35 g/m^3). The typhoons also affect Chl-a, with a mean concentration of 10 mg/m^3 and 30 mg/m^3 for pre- and post-typhoons, respectively. In addition, the normalized difference chlorophyll index (NDCI) is used in the Google Earth Engine platform for near-real time monitoring of cyanoHABs at 20 m spatial resolution. Satellite maps are key for detecting the distribution of the blooms due to the patchiness of the green algae species, which usually form scum and elongated slicks in the lake. Maximum records of bloom detection during the study period occur in the Central Bay, one of the lake sections with major aquaculture and fisheries activities. The Sentinel-2 mission improves synoptic mapping of cyanoHABs and enables trends in their extent and severity to be documented, which will assist and benefit the cost-effective management of Laguna Lake.



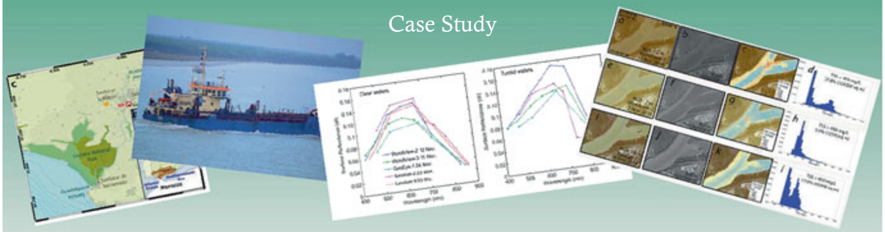
a) Normalized difference chlorophyll index-NDCI (dll) and b) false composite (NIR-Red-Green) on 3 November 2020 after Typhoon Goni; c) NDCI (dll) and d) false composite (NIR-Red-Green) on 13 November 2020 after Typhoon Vamco.

More information: *Caballero, I., & Navarro, G. (2021). Monitoring cyanoHABs and water quality in Laguna Lake (Philippines) with Sentinel-2 satellites during the 2020 Pacific typhoon season. Science of The Total Environment, 788, 147700.*

Acknowledgements*: This research was supported by the Spanish Ministry of Science, Innovation and Universities (MCIU), the State Research Agency (AEI), and the European Regional Development Fund (ERDF) in the frame of the Sen2Coast Project (RTI2018-098784-J-I00). We also thank Brian Skerry (https://brianskerry.com/) and Rhoy Cobilla for their photographs of the algal blooms.*

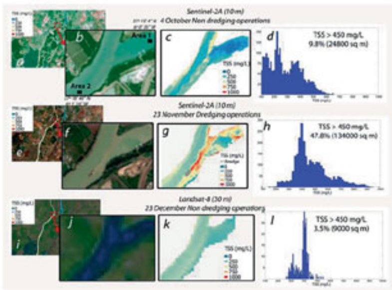
Dredging operations in an estuary

Case Study



Dredging activities in estuaries frequently cause deleterious environmental effects on the water quality, which can impact flora, fauna, and hydrodynamics, among others. A medium- and high-resolution satellite-based procedure is used in this study to monitor turbidity plumes generated during the dredging operations in the Guadalquivir estuary, a major estuarine system providing important ecosystem services in southwestern Europe. A multi-sensor scheme is evaluated using a combination of five public and commercial medium- and high-resolution satellites, including Landsat-8, Sentinel-2A, WorldView-2, WorldView-3, and GeoEye-1, with pixel sizes ranging from 30 m to 0.3 m. Applying a multi-conditional algorithm after the atmospheric correction of the optical imagery with ACOLITE, Sen2Cor and QUAC processors, the feasibility of monitoring suspended solids during dredging operations is demonstrated at a spatial resolution unachievable with traditional satellite-based ocean color sensors (>300m). The frame work can be used to map on-going, post and pre-dredging activities and assess Total Suspended Solids (TSS) anomalies caused by natural and anthropogenic processes in coastal and inland waters. These promising results are suitable for effectively improving the assessment of features relevant to environmental policies for the challenging coastal management, and may serve as a notable contribution to the Earth Observation Program.

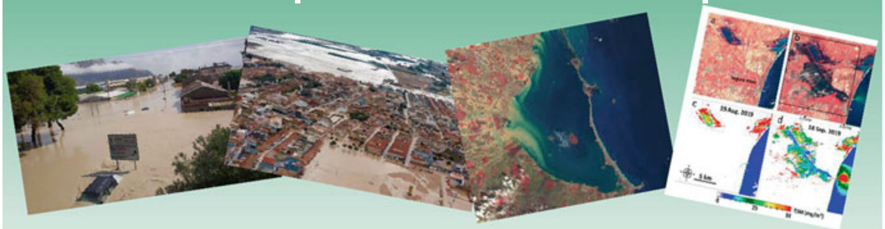
More information: *Caballero, I., Navarro, G., & Ruiz, J. (2018). Multi-platform assessment of turbidity plumes during dredging operations in a major estuarine system. International journal of applied earth observation and geoinformation, 68, 31-41.*



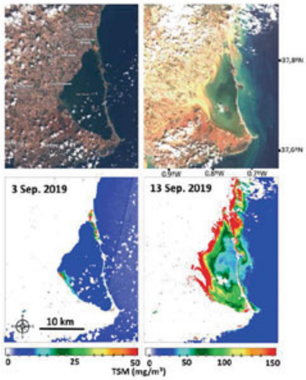
a) Map showing the Guadalquivir estuary RGB (bands 4-3-2) composite and TSS concentration of Sentinel-2 image at 10 m spatial resolution on 4 October 2016 with red rectangle delimiting the Region Of Interest (ROI) at the entrance of the Port of Seville, b) RGB composite, c) TSS concentration within the ROI, and d) Histogram of TSS within the ROI; e-h) the same for Sentinel-2 image on 23 November 2016. The hopper dredger and its shadow are masked in this scene; i-l) the same for Landsat-8 image at 30 m spatial resolution on 23 December 2016. Differences in TSS concentration between the main river channel (> 250 mg/L) and the parallel channel crossing the city of Seville (< 200 mg/L) are evident in the three images (a, e, i).

Acknowledgements: *The commercial imagery from WordlView-2/-3 and GeoEye-1 were provided by the European Space Agency in the framework of a Third Party Mission Project (id35116). This work was partially supported by the Projects P09-RNM-4853, PR11-RNM-7722, PIE201530I012 and CTM2014-58181-R.*

Catastrophic Floods in Spain



Flooding is among the most common natural disasters on our planet and one of the main causes of economic and human life loss worldwide. The devastating event in the Western Mediterranean during the second week of September 2019 is a clear case of this risk crystallization, when a record-breaking flood turned into a catastrophe in southeastern Spain surpassing previous all-time records. Using a straightforward approach with the Sentinel-2 twin satellites from the Copernicus Programme and the ACOLITE atmospheric correction processor, an initial approximation of the delineated flooded zones, including agriculture and urban areas, was accomplished in quasi-real time. The robust and flexible approach does not require ancillary data for rapid implementation. A composite of pre- and post-flood images was obtained to identify change detection and mask water pixels. Sentinel-2 identifies not only impacts on land but also on water ecosystem services, providing information on water quality deterioration and concentration of suspended matter in highly sensitive environments. Subsequent water quality deterioration occurred in large portions of the Mar Menor, the largest coastal lagoon in the Mediterranean. The present study demonstrates the potentials brought by the free and open-data policy of Sentinel-2, a valuable source of rapid synoptic spatio-temporal information at the local or regional scale to support scientists, managers, stakeholders, and society in general during and after the emergency.



Sentinel-2 RGB composites (red–green–blue) at 10 m spatial resolution showing the (a) before (3 September 2019) and (b) after (13 September 2019) of the flooding event in Murcia province (Spain). The high concentration of suspended material (TSM) in Mar Menor can be observed in the map (d) on 13 September with TSS > 200 mg/m^3 compared to the normal situation (c) on 3 September 2019 with minimum concentration (10 mg/m^3). White areas correspond to land, clouds, or cloud shadows masked after ACOLITE.

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