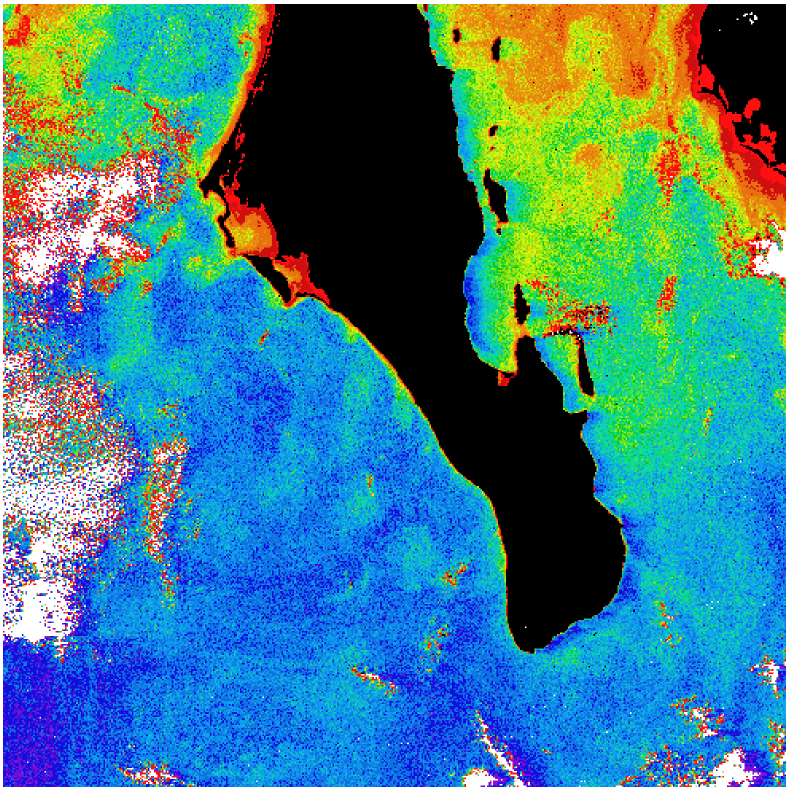
Classic CZCS Scenes

Chapter 11: On the Level – from Radiation to Scientific Imagery

The concept of using a sensor, mounted on a satellite, to observe the Earth—called "space-based" or "orbital" remote sensing to distinguish it from other types of remote sensing—seems simple enough. These sensors consist of two principal components: a detector component which receives radiation from the Earth, and a data processing component which translates detected radiation into digital data. The digital data can then be transmitted from the satellite to a receiving station on Earth.



CZCS image of southern Baja California, November 12, 1981

This image was created by combining several different wavelengths of light using an algorithm developed to determine chlorophyll levels in ocean water.

If that introduction makes the concept sound uncomplicated, it must be noted that the actual process requires advanced technology to convert the "raw" signal transmitted by the satellite into processed data and images that are meaningful and accurate. "Meaningful" implies that the data and images are realistic and interpretable, while "accurate" means that real scientific information can be gained from analysis of this information. Ensuring that the data is both meaningful and accurate is the primary challenge of space-based remote sensing.

This challenge has already been successfully met by numerous types of satellites and sensors. However, scientists and engineers are always striving to make the data more meaningful and more accurate. By improving data accuracy and content, the data can be employed in analyses and modeling that will in turn become more precise.

Light and the ocean – the basics

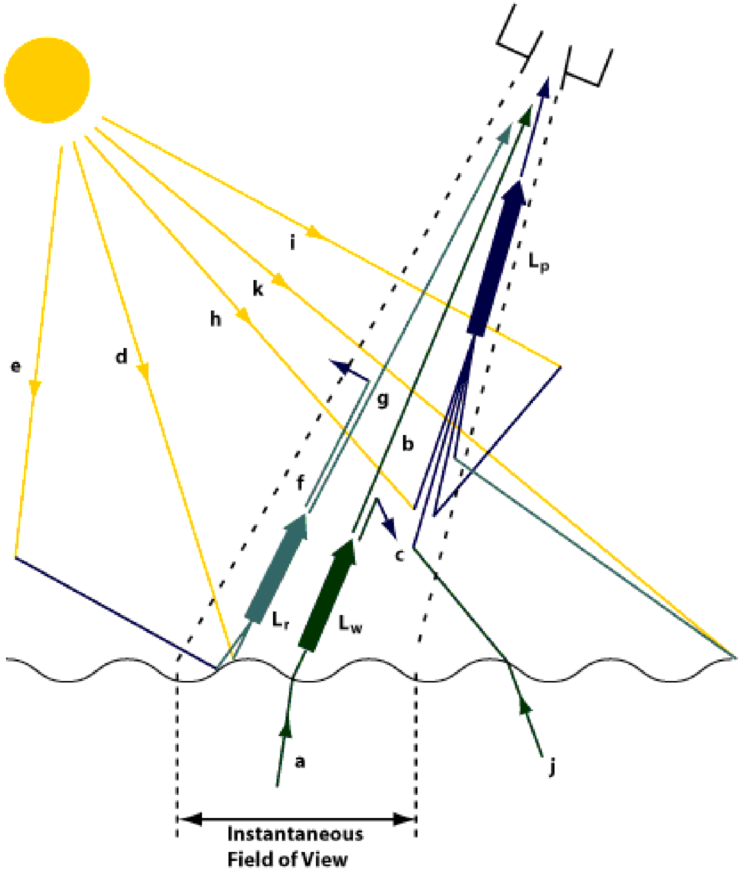
The goal of this discussion is to explain the basics of orbital **radiometry**, paying particular attention to ocean color radiometry. In the course of the discussion, the difficulties inherent in the process, as well as the advantages and disadvantages of this type of remote sensing, should be evident. **Radiometry** means the measurement of emitted radiation in specific ranges of the electromagnetic spectrum.

Starting at the beginning means starting at the Sun. The type of remote sensing discussed here detects visible light (VIS) or infrared thermal radiation (IR) being emitted from the surface of the Earth. The actual surface of the Earth consists of numerous different surfaces, all of which can interact with solar radiation. In some instances, solar radiation will be absorbed by a surface. Another type of interaction is reflection, where the incoming radiation is virtually identical to the outgoing radiation. In most cases, however, the radiation interacts with a surface such that modified radiation will be emitted from the surface. (Note: the general term for this type of remote sensing is **passive** remote sensing, to distinguish it from **active** remote sensing, where a signal is beamed from a satellite at the Earth and the reflected signal is detected.)

As an example, consider the leaves of a tree. Leaves contain chlorophyll, a pigment that uses light energy to produce carbon (the process of photosynthesis). The most common form of chlorophyll (**chlorophyll a**) absorbs in the blue and red regions of the visible spectrum and reflects in the green, so that the leaves of most trees appear green. Light from the Sun that hits the surface of a green leaf will be modified; the red and blue wavelengths are absorbed and the green wavelengths are reflected.

In the case of the thermal region of the spectrum, light may be absorbed by a surface and then radiated from the surface as heat, which is radiation in the far infrared portion of the electromagnetic spectrum. Detection of IR radiation can therefore be used to indicate the temperature of a surface. Variations in temperature can be mapped, which can provide more information. The temperature of the sea surface is variable, and this variability can provide information on current patterns, so maps of sea surface temperature are used by oceanographers to observe ocean currents (when clouds aren't in the way, of course).

Quite a bit happens to solar radiation when it enters the atmosphere and then impinges on the surface of the Earth. The next few paragraphs describe various paths of **photons** from the Sun within the Earth's environment. The main reason to refer to photons in this discussion is due to the fact that the detector systems of remote sensing instruments detect photons of various energies. What will be done here is to follow the possible paths taken by various photons from the Sun, to and from the Earth, and eventually to the detector of a satellite instrument. This diagram illustrates many of these possible paths.



In this figure, several different light pathways in the atmosphere are illustrated. **a)** The light path of the water-leaving radiance; **b)** attenuation of the water-leaving radiance; **c)** scattering of water-leaving radiance out of the sensor's field-of-view (FOV); **d)** Sun glint (reflection from the water surface); **e)** Sky glint (scattered light reflecting from the surface; **f)** scattering of reflected light out of the sensor's FOV; **g)** reflected light which is also attenuated towards the sensor; **h)** scattered light from the Sun which is directed toward the sensor; **i)** light which has already been scattered by the atmosphere, which is then scattered toward the sensor; **j)** water-leaving radiance originating out of the sensor FOV, but scattered toward the sensor; **k)** surface reflection out of the sensor FOV which is then scattered toward the sensor; **L_w**, total water-leaving radiance; **L_r**, radiance above the sea surface due to all surface reflection effects within the IFOV; and **L_p**, atmospheric path radiance. (This figure is adapted from Robinson, I.S., 1983: Satellite observations of ocean colour, *Philo. Trans. Royal Soc. of London, Series A*, Volume 309, 338-347.)

The simplest path a photon can take is the most direct one. The photon enters the atmosphere, hits a surface, is reflected, and bounces right back out into space, where it encounters the detector of a remote-sensing instrument. For ocean color remote sensing, this path presents a problem. Imagine the way that sunlight sparkles on the surface of water on a lake. Those sparkles are the direct reflections of light from the Sun into your eyes. Though such reflections are pretty, reflected light doesn't provide any information on what is actually **in** the water. When there is too much direct reflection, no information on what is in the water can be derived. For that reason, areas with too much reflection (called **sun glint**) are masked out of the data. Most ocean color sensors are designed to be tilted so that fewer directly-reflected photons will find their way to the detector.

The next path is the main one of interest to science. A photon enters the atmosphere, encounters a surface, is modified in some way, and then is radiated up to the detector in space. The example of a tree leaf was already given above. In water, photons enter the ocean, and some wavelengths are absorbed while others reflect off particles suspended in the water. The most important path in the ocean is the absorption of specific wavelengths of light by the chlorophyll present in phytoplankton cells, so that the remaining radiation is an indication of how much light was absorbed. The net result is that a only small percentage of the light that enters the water (the **downwelling irradiance**) is redirected back toward the surface (the **upwelling radiance**). If the upwelling radiance actually leaves the surface and heads toward space—even though all of it doesn't get there—it is termed the **water-leaving radiance**. Water-leaving radiance is what ocean color sensors are specifically designed to measure.

Those two paths are fairly direct. However, quite a bit of the light that enters the atmosphere and ocean is **scattered**, because it interacts with air molecules, dust and other substances suspended in the atmosphere, or substances and particles in the ocean. Light scattering (particularly the preferential scattering of higher frequency light) is what causes the light blue color of the sky, or the intense blue of very clear, deep water. There are numerous scattering paths that photons can take. The path a photon takes before encountering a surface isn't important; the important path is the one it follows after leaving the surface. For example, many of the water-leaving radiance photons will be scattered by the atmosphere and never make it to the detector on the satellite. Many more photons won't even reach the ocean, but will be scattered by the atmosphere back to the detector (or they will reflect off clouds). Aerosols or haze in the atmosphere will also partially interfere with the photons radiating toward the detector, perhaps modifying their wavelength by absorption and re-radiation, or by scattering the light even more.

The net result of all these interactions is that for an orbital sensor aimed directly at the ocean, about 10% of the total light it detects is water-leaving radiance. The other 90% of the light is due to atmospheric effects. (Since land is more reflective than the ocean, a sensor aimed at land receives a greater percentage of light from land surfaces and a lesser percentage from the atmosphere.) Corrections must be applied to the data to remove this atmospheric radiance, allowing accurate measurement of the amount and color of light exiting the ocean surface. This is where data processing comes in. An optical model of the atmosphere above the ocean can be formulated, using such inputs as the surface pressure and the transmission of light through the atmosphere at certain wavelengths. Using this optical model, the radiance the satellite "sees" can be corrected for the influence of the atmosphere, theoretically leaving only the water-leaving radiance!

Data Product Levels

In order for remote-sensing data to be useful, the data is processed through several "levels". The definitions of the data levels were agreed upon by the National Academy of Sciences Committee on Data Management, Archiving, and Computing (CODMAC). For precisely worded definitions, the *EOS Data Product Levels* show below were formulated. (Note that the definitions are not specific to the Earth Observing System (EOS), but are applicable to all types of remote sensing data.)

Level 0

Level 0 data products are reconstructed, unprocessed instrument/payload data at full resolution; any and all communications artifacts, e.g. synchronization frames, communications headers, duplicate data removed.

Level 1A

Level 1a data products are reconstructed, unprocessed instrument data at full resolution, time-referenced, and annotated with ancillary information, including radiometric and geometric calibration coefficients and georeferencing parameters, e.g., platform ephemeris, computed and appended but not applied to the Level 0 data.

Level 1B

Level 1A data that have been processed to sensor units (not all instruments will have a Level 1B equivalent).

Level 2

Level 2 data products are derived geophysical variables at the same resolution and location as the Level 1 source data.

Level 3

Level 3 data products are variables mapped on uniform space-time grid scales, usually with some completeness and consistency.

Level 4

Level 4 data products are model output or results from analyses of lower level data, e.g. variables derived from multiple measurements.

Before there has been any data processing, the data is termed **raw data**. Raw data simply consists of the electronic signal that is produced when photons of light are detected by the instrument. Depending on how the instrument looks at the Earth (which is determined by the way the instrument works), the signals are assigned to **picture elements**, or **pixels**, the basic pieces of a remote sensing image.

The first level above raw data is Level 0. Navigational data and other relevant information from the satellite are assigned to the detected signal. This data ensures that the corresponding region on Earth that was being scanned from space is known. The electronic signal has not yet been converted to measured radiances.

To produce Level 1 data, the electronic signal from the detector is converted to radiances measured **at the satellite**, and information from the satellite's on-board calibration routine is added to the data. There are many different ways to maintain the accurate calibration of a satellite instrument. One of the most common calibration methods has the sensor scan a "source" possessing a known, consistent radiance. The Sea-viewing Wide Field-of-view Sensor (SeaWiFS), NASA's ocean color instrument that followed the CZCS, scanned a solar (sunlight) diffuser possessing a known radiance, and the sensor also performed a lunar calibration by viewing the Moon at a certain phase. (SeaWiFS, like most other remote-sensing instruments, was accurately calibrated before launch. On-board calibration methods such as these strive to insure that the calibration of the instrument is known throughout the mission.) Once the radiances are determined, the navigation data can be used to generate an image. However, more information must be used to make this image relevant to conditions at the surface of the Earth.

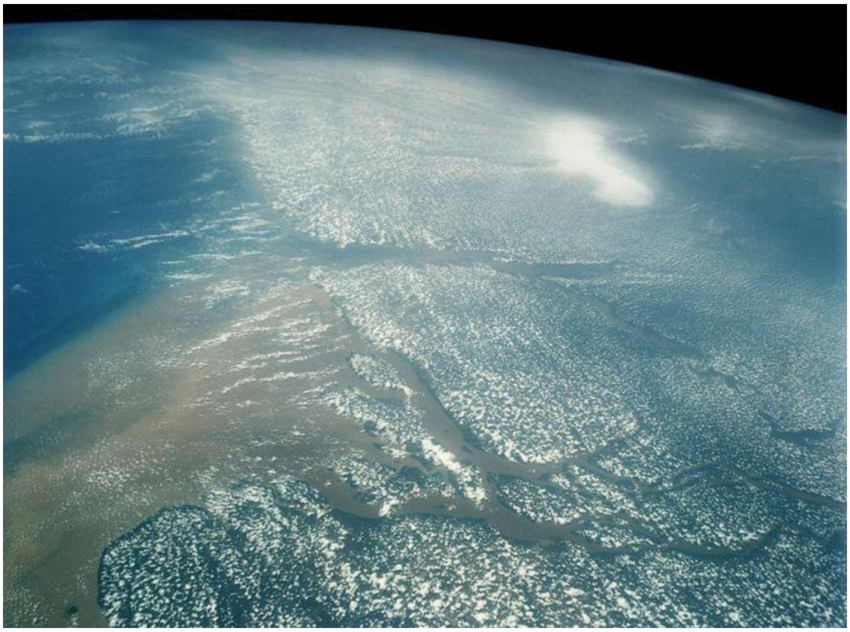
The conversion from Level 1 data to Level 2 **data products** applies sensor calibration data and atmospheric correction to calculate Earth surface radiances from the radiances measured at the satellite. The ongoing calibration routines ensure that the radiances will always represent the same absolute radiance, despite possible changes in the optical system of the instrument. Other checks on the quality of the data will also be applied here. Based on the radiances measured at the satellite, **masks** indicating the presence of clouds, land, and perhaps sea ice will be added to the data stream. **Flags** may also be added to indicate unusual conditions or anomalous data.

Several different kinds of data are used to derive the most accurate geophysical parameters. Data from sources other than the satellite itself is termed **ancillary data**. For ocean color, examples of ancillary data are wind speed (used to calculate sun glint masks and the presence of whitecaps), ozone (used for atmospheric correction, as ozone absorbs some light), and atmospheric pressure.

Once the surface radiances are calculated, new analytical routines can be applied that convert this information into different types of **geophysical parameters**, or products. For land surfaces, the radiances may indicate the different types of surfaces or the amount of land covered by vegetation. For ocean color, the radiances can be used to calculate the concentration of chlorophyll in the water, or the amount of suspended sediments. Thus, Level 2 data includes both Earth surface radiances and calculated geophysical parameters.

The conversion of radiances to geophysical products employs algorithms developed by painstaking research. Highly accurate measurements of radiation are made, using either radiometers or spectrometers, to characterize the radiative signature of a particular environment. For ocean color data, such radiometers must be immersed in the open ocean, and they will measure both the incoming (downwelling) and outgoing (upwelling) radiation. The instruments measure the variability of light at many different wavelengths (particularly those wavelengths that the sensor in space has been designed to measure). At the same time, samples of the environment, which may mean vegetation or soil on land, or water samples from the ocean, are examined.

In seawater, the concentrations of phytoplankton and their chlorophyll will be analyzed, and these concentrations will then be correlated with the measured radiances. As these measurements are made, researchers hope to find consistent relationships between the radiances and the surface variables that are being measured, which will allow them to construct an *algorithm*. The algorithm will calculate a specific variable, such as chlorophyll concentration, based solely on the radiance data. Satellite data is then used in these algorithms to calculate the geophysical parameters over large areas of the Earth.



Astronaut photograph of the Amazon River delta and Atlantic Ocean.

This is definitely a complex process, and it may be difficult to visualize. Now examine the picture on the previous page of the Amazon River delta, which was taken by astronauts. The ocean currents in this region carry the muddy water of the Amazon along the coast, and it can be easily distinguished from the clear blue water of the ocean. It's obvious that the brownish water along the coast has much different optical characteristics than the clear blue water further out to sea. The goal of ocean color remote sensing algorithms is to distinguish different types of water, and the constituents that determine a particular color. Ideally, a useful algorithm would calculate the concentration of suspended particulates in the muddy water, and the concentration of chlorophyll in both turbid and clear water. [By the way, oceanographers use the term Case 1 water for clear ocean water. Coastal waters that may range from reddish-brown (sediments) to green (phytoplankton chlorophyll), and numerous hues in between, are termed Case 2 waters.]

Now picture a forest composed of only one species of tree, or a part of the ocean with one kind of phytoplankton. Both of these environments will have a fairly uniform color. In these cases, a fairly simple relationship exists between the color that the satellite observes and the density of either trees or phytoplankton. Ratios of light intensity detected at various wavelengths of the VIS/IR spectrum have been used in algorithms to calculate vegetation density or chlorophyll concentration. However, if you have an area with many different types of plants and soils, or water with different species of phytoplankton as well as sediments, it becomes much more difficult to find simple relationships between optical properties and geophysical characteristics. However, that's still the goal of algorithms which calculate Level 2 geophysical products.

Maintaining Data Accuracy

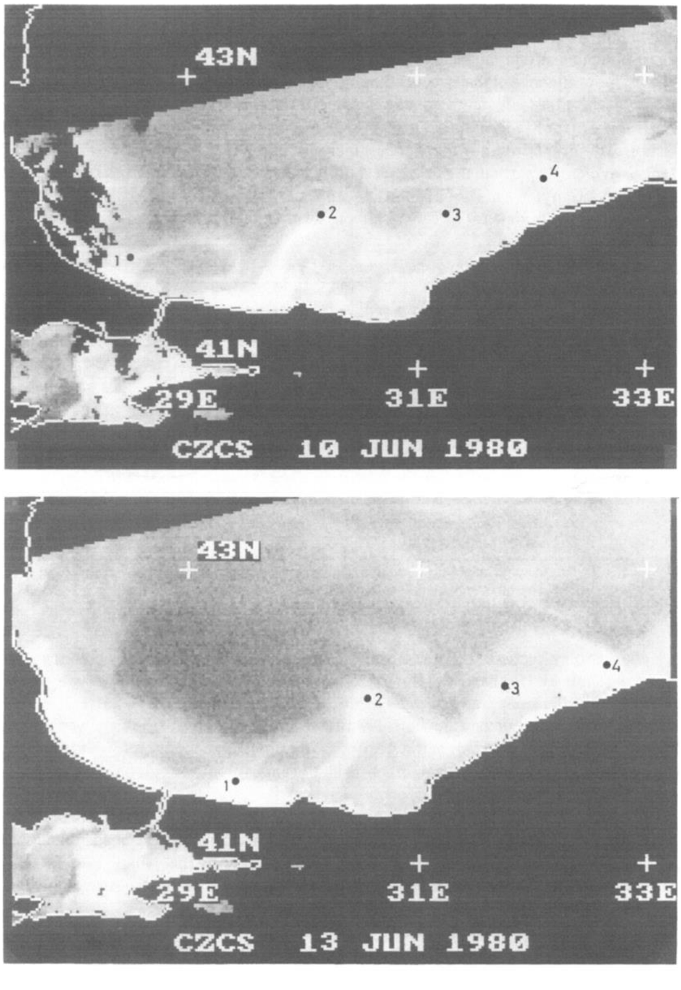
One other aspect of this topic is the fact that instruments in space tend to change over time, and usually can't be taken back to the laboratory to be re-calibrated. Unfortunately, chlorophyll algorithms rely on very accurate measurements of radiance. So another challenge of remote sensing is to make sure that the calibration of the instrument is known to a very high level of precision. As mentioned previously, several different ways of calibrating these sensors while the satellite is in space have been devised. However, these methods don't always work, and scientists have been forced to come up with clever ways to maintain the quality of the data. The next paragraph describes one such situation.

The Coastal Zone Color Scanner (CZCS) carried lamps intended for use as on-board radiance sources for calibration. However, the reliability of these lamps became questionable. For that reason, and also due to degradation in the sensitivity of the detectors in the CZCS over time, scientists devised a way to calibrate the instrument based on the data it was receiving. Their method relied on the fact that the amount of light leaving an area of the ocean with very clear water is fairly constant. By knowing this amount of light, the "clear-water radiance" of a certain pixel was used as the reference for all of the other pixels in a given CZCS image.

Even though this calibration method was imperfect, partly because it relied on the "clearest" water pixel in a given image, it was employed to produce a consistent data set from all the data collected in the eight years of CZCS operation.

It should now be clear that utilizing photons observed by a satellite sensor and converting them to meaningful geophysical information is a fairly complex operation. That's why so much discussion was devoted to Level 2 data. However, there is one more data level—Level 3. Level 3 data is accumulated data, collected according to the corresponding location on the surface of the Earth. The Earth is divided up into cells on a grid, which are called **bins**. All of the data for a grid cell collected daily, weekly, monthly, or yearly is put into a bin. Collection of data in this systematic manner allows the data to be treated statistically, and also allows data from certain regions to be grouped together. A distinction is frequently made between spatial bins and temporal bins, which means that data can be organized according to either where the data was received from, or the time interval during which it was collected.

So now you know the following about orbital remote sensing of the Earth:
- what you see isn't necessarily what you want to know; and
- getting from what you see to what you want to know requires a lot of careful work in between.



Two examples of CZCS Level 2 data are shown at left. These two images of the southern Black Sea and Sea of Marmara were acquired on June 10 and 13, 1980. The data shown here is the water-leaving radiance at 520 nm.