Viewed from Above: An Learning Diary on Remote Sensing & Earth Observation

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Table of contents

Hello...[unfinished]

...from a novice to another!

Part I.

Making sense of Remote Sensing

1. Intro to Remote Sensing

1.1. Summary

Remote Sensing uses satellites, planes, drones, etc., as our aerial eyes, piecing together a portrait of our planet through light and data and revolutionising how we understand and interact with it.

Sensors, well, 'sense' Earth in two ways: Some passively listen to sunlight reflected off our planet's surface (i.e., *passive sensors*), while others actively send their own signals and capture the echoes (i.e., *active sensors*). By that definition, the human eye is a type of passive sensors!

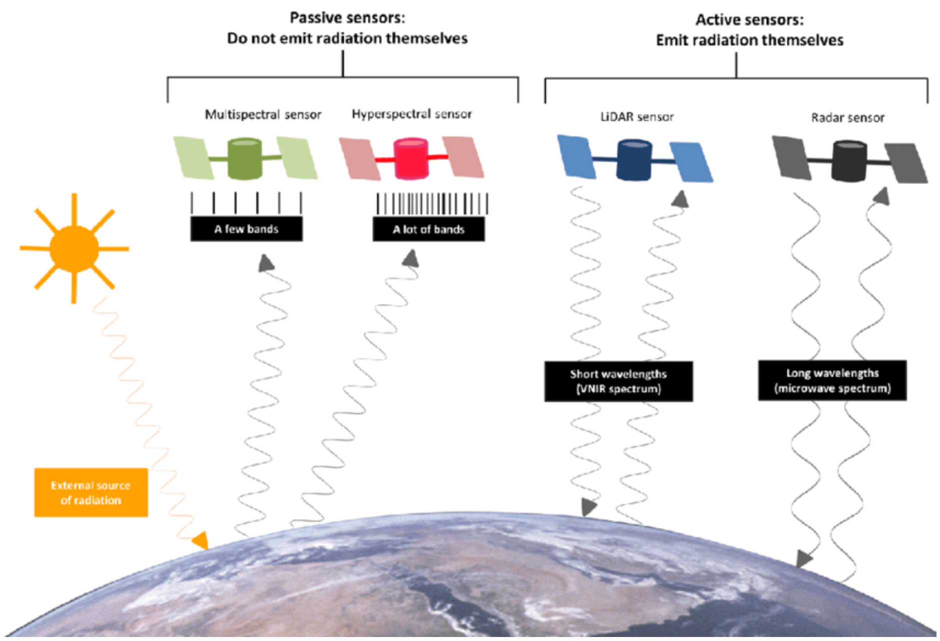


Figure 1.1.: Active vs Passive Remote Sensing (Earth Science Data Systems 2019).

These sensors interpret a fascinating language of light, both invisible and visible, known as the *electromagnetic spectrum.*

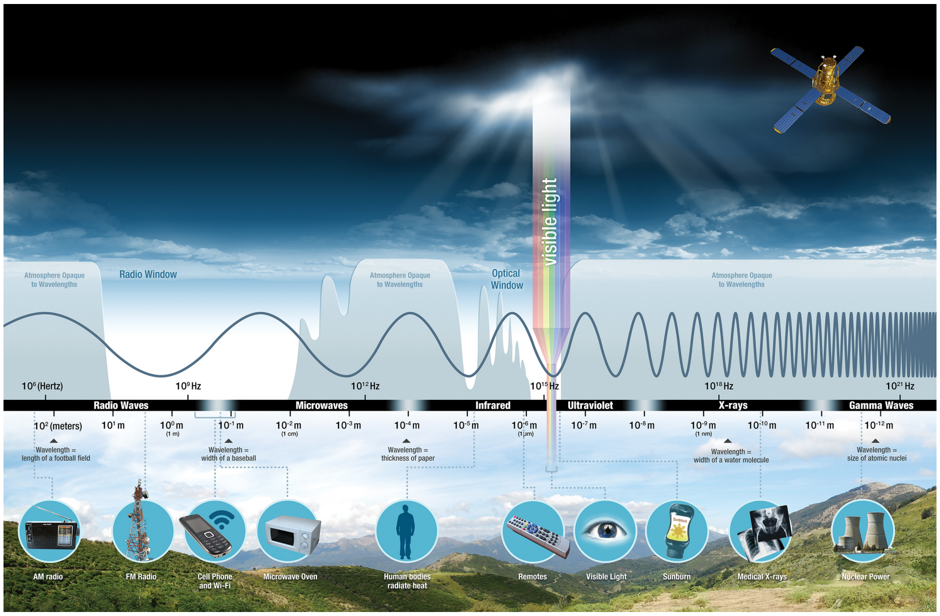


Figure 1.2.: The Electromagnetic Spectrum (EMS). Credit: NASA Science

Electromagnetic radiation moves as waves as perpendicular electric and magnetic field with a wavelength: `= c/v` where:

- = **wavelength**, the distance between two crests
- `c` = velocity of light 3 x 10^8 m/sec
- `v` = frequency, rate of oscillation (full oscillations in a time unit)

Different materials reflect unique wavelengths in this spectrum, allowing us to identify them, like decoding DNA!

But the information that sensors receive isn't just about colour. Remote sensing data has its own "resolution" recipe, encompassing:

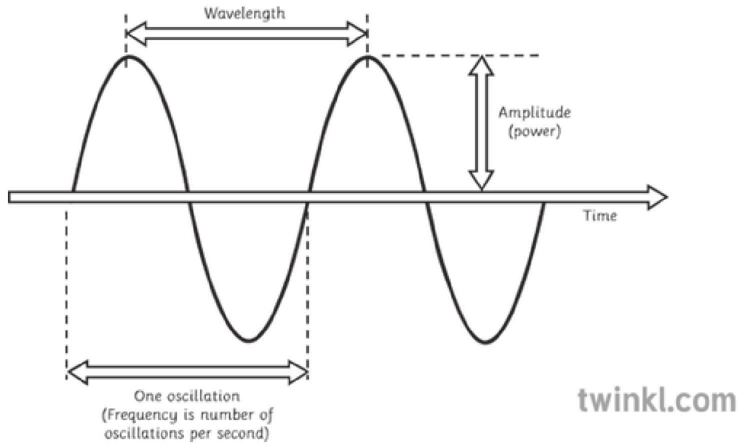


Figure 1.3.: Wavelength vs. Oscillation

- **Spectral:** How EMS bands (i.e., the range within the EMS) the sensor can hear, revealing more detail with each additional band.
- **Spatial:** The size of each pixel in the image, ranging from centimetres to kilometres, offers varying detail levels.
- **Temporal:** How often the sensor revisits the same area, providing a dynamic view of changes over time.
- **Radiometric:** The range of brightness levels captured, painting a vibrant and accurate picture.

Depending on the purpose, each sensor is equipped to have better resolution of one type over the other. For example, sensors with a high spatial resolution of 5m (i.e., each pixel is 10x10 on the ground) will have a lower spectral resolution (i.e., capturing only a narrow range of the EMS) ("Remote Sensing, Satellite Imaging Technology | Satellite Imaging Corp" n.d.)

1.2. Application

Remote Sensing has many transformative applications in the realm of Urban Analytics. Think of it as an X-ray for cities, revealing hidden patterns and empowering informed decision-making by city planners, urban designers, and public officials to make swift and informed decisions to improve the lives of millions of urbanites.

Here are some examples of the use of Remote Sensing in urban analytics research

1. **Mapping Urban Growth:** By tracking changes in the built environment over time, we can identify sprawling suburbs, monitor urban expansion, and plan for infrastructure needs. Recent works have used a diverse source of high-resolution Remote Sensing data (2m) to train a machine-learning model to extract 'urbanised' areas more robustly compared to a previous methodology using only medium-resolution images. (Wang et al. 2021)

2. **Predicting Floods with Foresight:** Analysing land cover and terrain, it anticipates where water will flow, safeguarding communities from harm while also estimating potential damage. This type of risk assessment is highly relevant not only in climate science and the public sector but also among insurance companies who make use of SAR satellite data (for through-cloud vision) combined with other spatial data sets to assess risk and process claims (Schumann et al. 2023)

3. **Energy Efficiency:** Identifying heat island effects and understanding building energy consumption through thermal imaging empowers planners to design sustainable cities and researchers. Remote Sensing data is a key component in Urban Climate Models such as UrbCLIM by VITO, a Belgian research organisation, which aims to create an interactive tool providing high-resolution urban heat maps

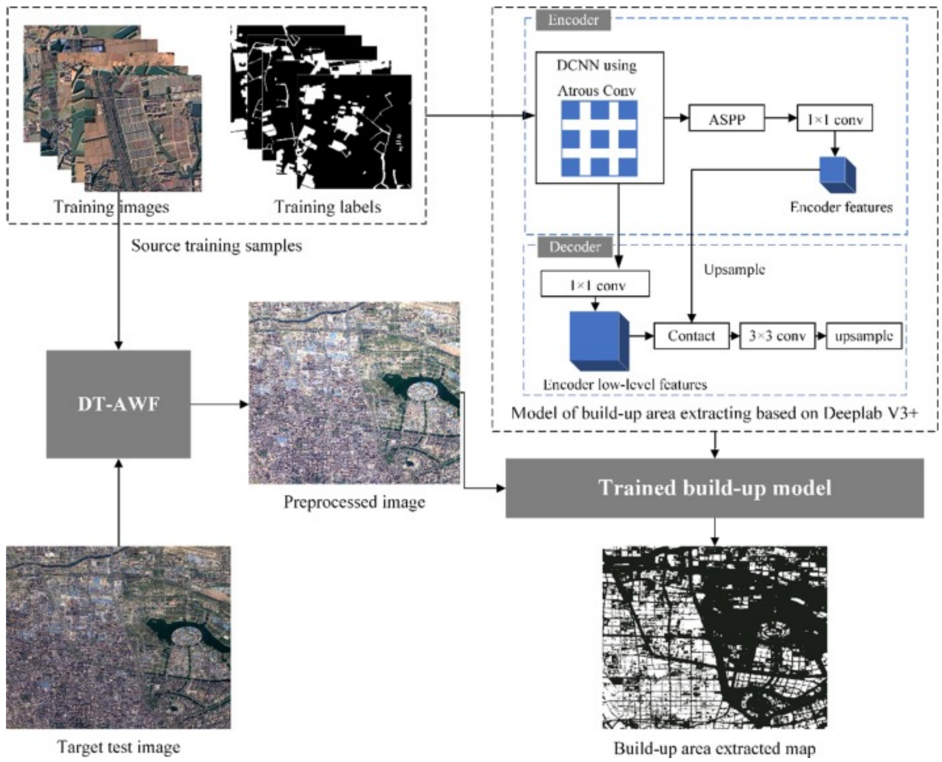


Figure 1.4.: Transferable built-up area extraction (TBUAE) framework to map urbanised areas

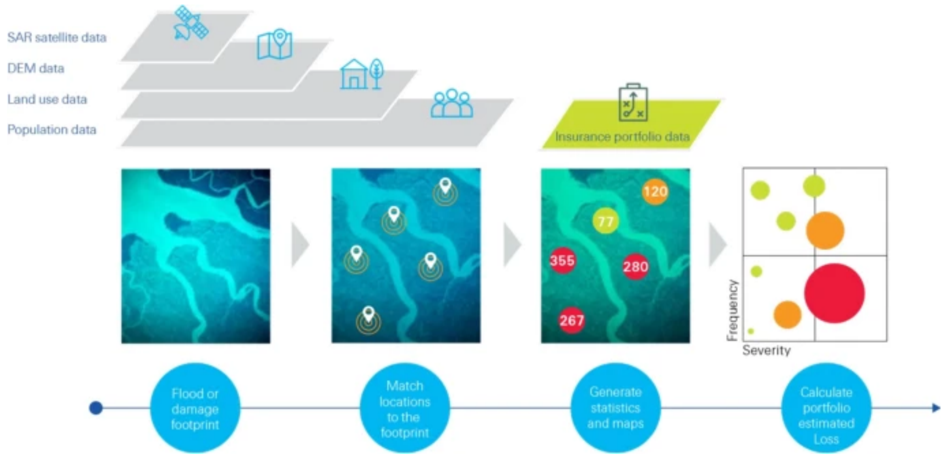


Figure 1.5.: Remote sensing data can be used to estimate flood extent and to derive individual risk level damage estimates.

> and predict their evolution under future climate conditions. ("DestinE for Human Heat Stress: ECMWF Use Case to Tackle Urban Heat Islands" n.d.)

This is just the beginning. Remote sensing transforms how we understand and manage our cities, paving the way for a healthier, smarter, and more sustainable urban future.

1.3. Reflection

My first foray into the world of Remote Sensing was eye-opening. For the uninitiated, it is easy to assume that remote sensing purely means orthophotography satellite images that one might see using platforms such as Google Maps, i.e. as if the only thing that sensors do were to snap a simple photo of the planet like a phone camera.

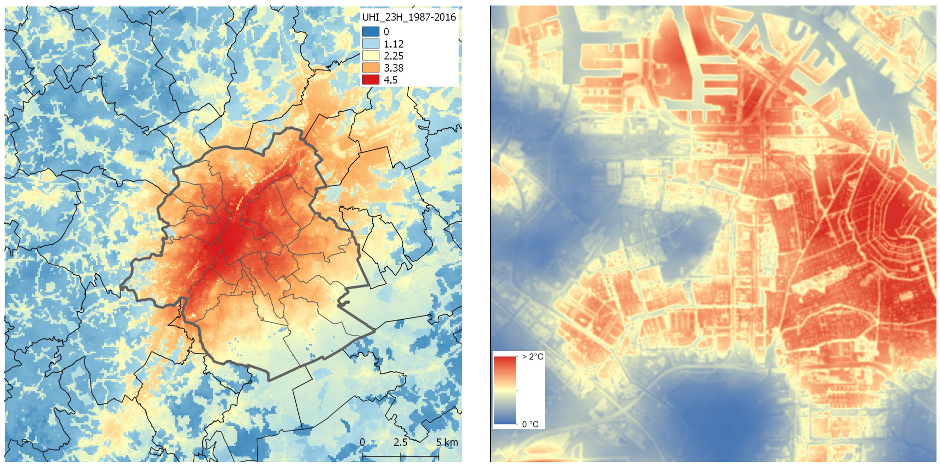


Figure 1.6.: **Left:** Average 2m air temperature at 23h (moment of max Urban Heat Islands) during all summer months of 1987- 2016. **Right:** UrbCLIM climate model's output field showing the average daily maximum urban heat island intensity for Amsterdam

In reality, it unlocks unseen depths of data beyond mere human perception, not just high-resolution photographs and more spectral signatures, where each pixel holds a universe of information. Building a true-colour composite from all these layers (so that our limited human vision can perceive them) was like seeing the world through a brand-new lens.

I am particularly excited to get started with Google Earth Engine later on as the primary gateway to access the wealth of remote sensing data and analytics with more ease to solve specific problems facing our world today.

2. A peek into the LiDAR technology

Or, how to 3D print a city

Having understood how sensors work in theory, we can now shift our view to appreciate how one of them in particular, LiDAR (**Li**ght **D**etection **a**nd **R**anging), is deployed in practice and can benefit us in an emerging sector: *Autonomous Vehicles.*

3. Corrections and Enhancements

3.1. Summary

Raw data from sensors are rarely immediately usable without being corrected for various interferences and effects. Common correction methods are geometric and topographic corrections and radiometric and atmospheric corrections. Finally, enhancement methods help us highlight values of interest that pertain to our research scope.

3.1.1. Radiometric and Atmospheric corrections

These processes describe translating raw light data from the sensor into ‘true’ information on the surface’s reflectance property without interference from the light source and the atmosphere.

- **Radiometric calibration** is the conversion from raw Digital Number (raw, no units) to Spectral Radiance via a linear transformation $L_\lambda = Bias + (Gain * DN)$. Radiance most often has units of watt/(steradian/square meter)
- **Atmospheric correction** is the next step:
  - **TOA Radiance-to-Reflectance** correction removes the effects of the light source (e.g. the sun) by calibrating radiation going down (irradiance) and up (radiance). TOA Reflectance still affects the atmosphere and the surface material. If irradiance is equal to radiance, we call this *hemispheric reflectance.*

- **TOA-to-BOA Reflectance** correction removes the effects of the atmospheric conditions, leaving us with just data on the surface materials. If shadows and directional effects on reflectance have been dealt with, we get what is called *true reflectance*; if not, it is called *apparent reflectance.*

Atmospheric correction deserves our attention, considering the effect of atmospheric scattering on the final results. Absorption and scattering create the haze, which reduces the contrast and can create the "adjacency effect", whereby radiance from pixels nearby is mixed into pixels of interest. Atmospheric correction to obtain actual reflectance is not always necessary, for example, for classifying a single image, working on composite images, etc. There are two types of atmospheric correction: -

- **Relative:** normalise intensities of different bands within a single image or from many dates to one date. This can be done via *Dark Object Subtraction (DOS)* or *Pseudo-invariant Features (PIFs).*
- **Absolute:** change digital brightness values into scaled surface reflectance. We can then compare these scaled surface reflectance values across the planet through atmospheric radiative transfer models (i.e. summer, tropical) or *Empirical Line Correction.*

3.1.2. Geometric and topographic corrections

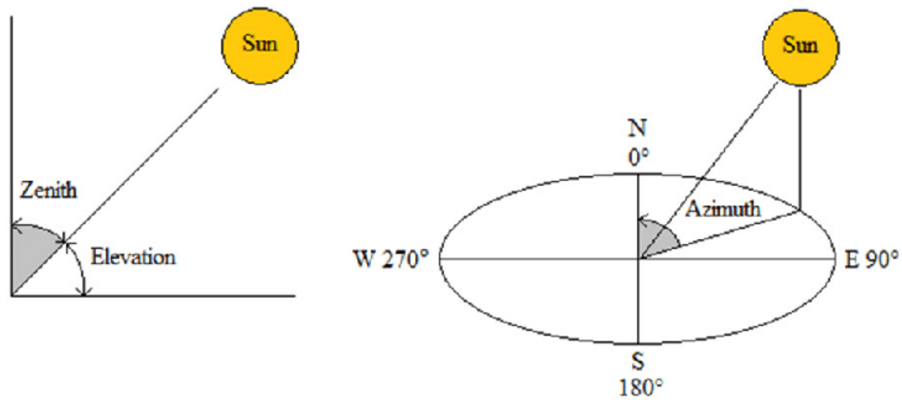
These are subsets of Georectification, which gives coordinates to an image and accounts for view angle, topography, wind disturbance, Earth rotation, etc., distorting the resultant image's geometry.

Topographic correction corrects the view angle of the image so that it is nadir (i.e., directly top-down). Important concepts to get familiar with for orthorectification are:

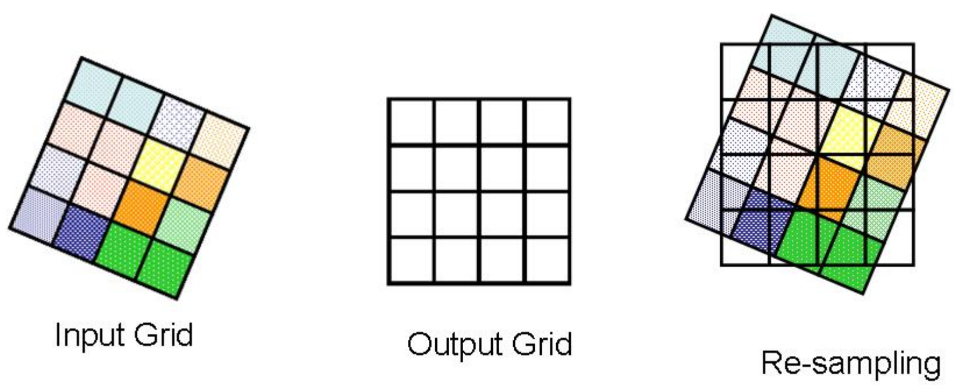
- *Solar azimuth:* compass angle of the sun (N =0°) 90° (E) at sunrise and 270° (W) at sunset.

Figure 3.1.: Example of LEDAPS atmospheric correction. (a) Top-of-atmosphere (TOA) reflectance composite (bands 3,2,1) for Landsat-7 ETM+ image of San Francisco Bay (July 7, 1999); (b) Surface reflectance composite.

- *Solar zenith:* angle of local zenith (above the point on the ground) and sun from vertical (90° - elevation)



Geometric correction effectively 'grounds' the images into a georeferenced final product (i.e., with a coordinate). We identify Ground Control Points (GPS) to match known points in the image and a reference dataset. We then model the coordinates to give geometric transformation coefficients (linear regression). It effectively resembles fitting old maps into a digital version.



3.1.3. Joining and Enhancements

To join (i.e., 'mosaicking'), within the overlap area (20-30%), a representative sample is taken, a histogram is extracted from the base image, which is then applied to other images using a **histogram matching algorithm** to blend the brightness values of the two images ('feathering')

Finally, after all the corrections, there are still many enhancements that can improve or accentuate the visual results depending on the purpose of the research:

- *Contrast enhancement* to accentuate reflectance values that are close to each other
- *Ratio calculation* calculates pixel value as a ratio of different bands (e.g. Normalised Burn Ratio)
- *Filtering* is the use of low-pass filters that average (i.e., smooth) the data or high-pass filters that enhance the variances between features. Filtering is used to perform texture and edge detection.
- *PCA* transforms multi-spectral data into uncorrelated datasets. Multi-date overlay PCA is a way to detect change efficiently.
- *Fusion* entails fusing images/data from multiple sensors to improve details, enable better classification, or downsample.

3.2. Application

Despite having delved a lot into corrections, it is worth noting that standard remote sensing products now come corrected (Level-2, or "Analysis Ready Data", ARD). In contrast, products derived from corrected ones are called Level-3. Research that works directly with Level-1 products often seeks to refine the correction methodology to transform them into ARDs (Coluzzi et al. 2018)

Enhancements made to ARD (i.e. Level-3 products) represent a proliferating field to survey, thanks to its wealth of innovative applications of a single or combinations of techniques, depending on the task at hand. According to recent research that made use of remote sensing data, there seem to be two main umbrella objectives researchers have when considering which enhancement methods to employ:

1. *Visualisation:* Visual enhancement essentially accentuates the desired subject vs. other details. Contrast stretching to make images appear brighter is often done without much fanfare but is an essential step in using remote sensing data as an artefact perceptible in print to the human eyes. However, image enhancement using band ratio is widely used to highlight certain objects, with indices including NDVI, SAVI, etc., for Vegetation or NDWI, SWI, etc., for Water and Snow. A combination of indices can also be used to produce a composite ratio that can best visualise the desired study area, which was how Macedo et al. (2018) was able to map the holm oak above-ground biomass over a large area with different atmospheric conditions.
2. *Feature extraction:* Many researchers seek to extract novel datasets from remote sensing data for various purposes, including training machine learning models to do the same (and better) for a larger region or globally. This objective is related to but ultimately distinguished from the above because the output is not a cartographic product but a dataset. The main difficulty when tackling this is to classify accurately (avoid false negatives and positives) while retaining the depth of information in each pixel. Li et al. (2022) proposed a pyramid feature extraction (PFE) to construct multi-scale representations of buildings, in which convolutional neural networks were applied on satellite images already gone through a combination of edge and texture detection, which were then again applied to subsequent output in the workflow.

3.3. Reflection

My initial knowledge of remote sensing was limited, but this exploration proved insightful and rewarding. The vast amount of information obtainable from raw multi-spectral data is impressive and somewhat little-appreciated outside of the geospatial community.

Therefore, democratising remote sensing data and technological advancements will empower research on Earth's surface, surpassing local data collection, which is uneven and ununified by nature. Instead, remote sensing can be performed globally if the correct adjustments for the atmosphere and enhancements to fit the objectives are made.

However, while this is an untapped data source, there are two hurdles to overcome before they may be fully utilised.

- Technical competence: Remote sensing is jargon-filled, with each discipline adopting its best practice to harness the data, making the barrier to entry higher than that of other types of data analysis work. Standardisation of industry-agnostic workflow and training may be vital to upskilling geospatial analysts to work more natively with remote sensing data.
- High-resolution EO data are mostly not free and reserved for governmental/military use. High-quality EO data (multispectral, high spatial resolution, frequent, etc.) also depends on localities. Sophisticated enhancement techniques may help bridge the gap by fusing existing datasets.

Part II.

Resources

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