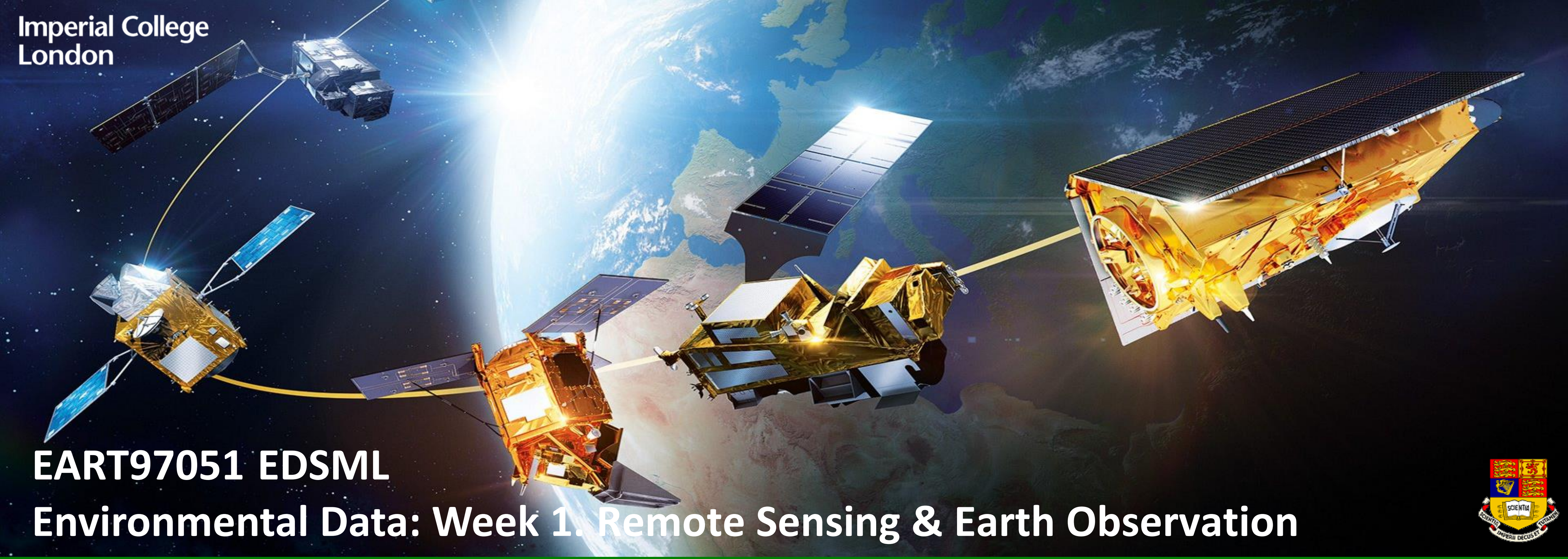
Imperial College London



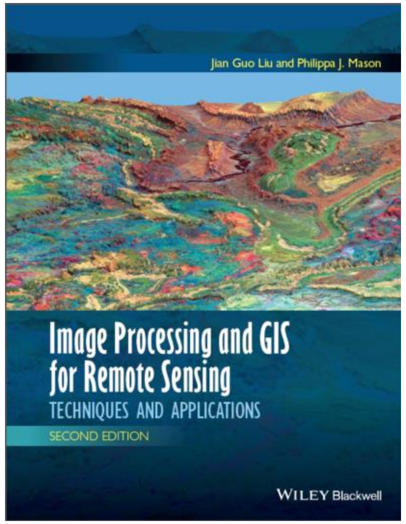
EART97051 EDSML
Environmental Data: Week 1. Remote Sensing & Earth Observation

1b Digital image display, point operations and contrast enhancement

Dr Philippa J. Mason

Senior Lecturer in Planetary Remote Sensing,
Department of Earth Science & Engineering, Imperial College London, SW7 2AZ, UK
E-mail: p.j.mason@ic.ac.uk

Recommended References



Jian Guo Liu and **Philippa Mason**, 2016, *Image Processing and GIS for Remote Sensing – Techniques and Applications*, Second Edition, 472p, ISBN: 978-1-118-72420-0, March 2016, Wiley-Blackwel. Contains all the mathematical background for image processing of all kinds of digital remotely sensed imagery. http://eu.wiley.com/WileyCDA/WileyTitle/productCd-1118724208.html

Other fundamentals of digital image processing techniques (non-ML/DL)

Gonzalez, R. C., Rafael, C. at al.,, 2019, *Digital Image Processing (pdf).*

Jensen, J. R.2016, Introductory Digital Image Processing – A Remote Sensing Perspective.

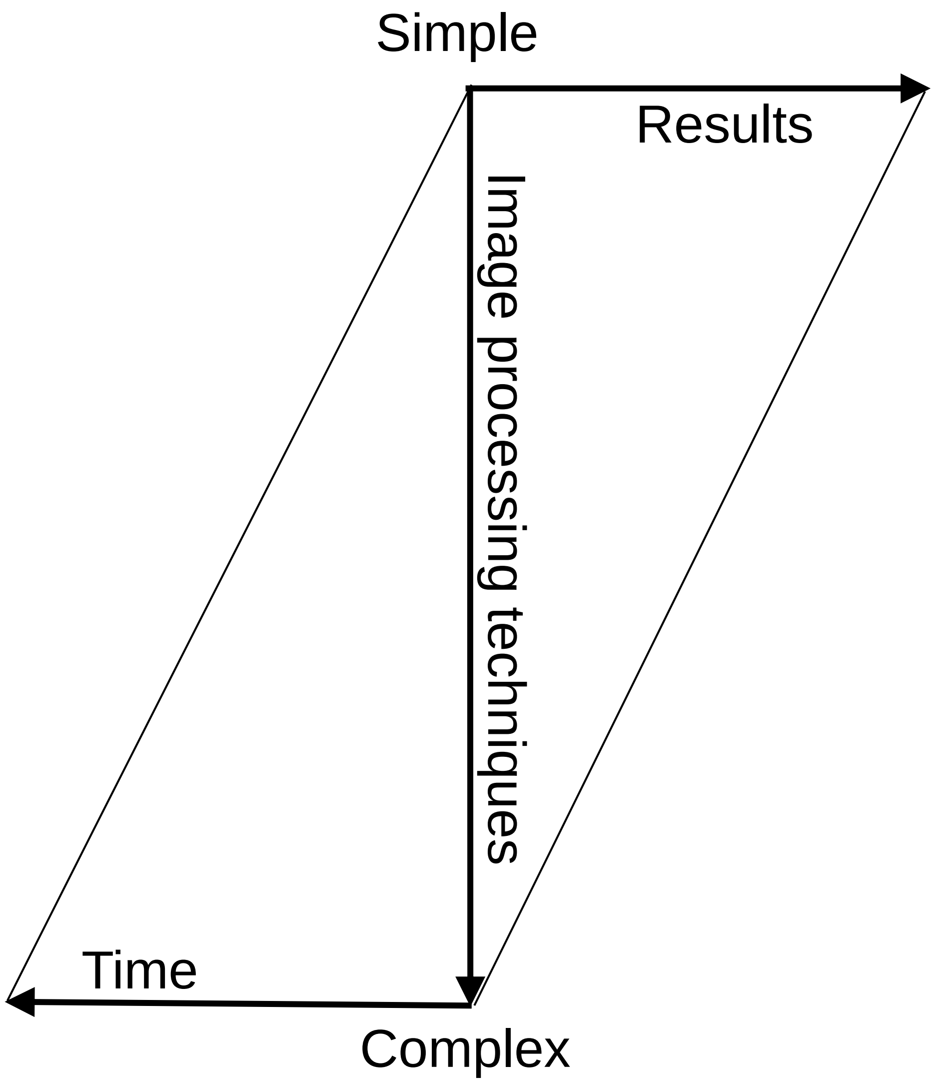
Richards, J. A., 2013, *Remote Sensing Digital Image Analysis: an Introduction.* (3rd Edition)

Mather, P. M., 2011, *Computer Processing of Remotely-Sensed Images, 4th edition*

Schowengerdt, R. A., 2006, *Remote Sensing: Models and Methods for Image Processing*

Niblack, W., 1986, *An introduction to digital image processing (old but really good)*

Image Processing



Warning:
Image processing can never increase the information contained in the original image dataset!

A successful image processing result is not necessarily proportional to the time/effort spent!

On the contrary, you may spend very little time & yet achieve the most useful results with simple techniques OR you could spend a lot of time designing complicated techniques and achieve a very little!

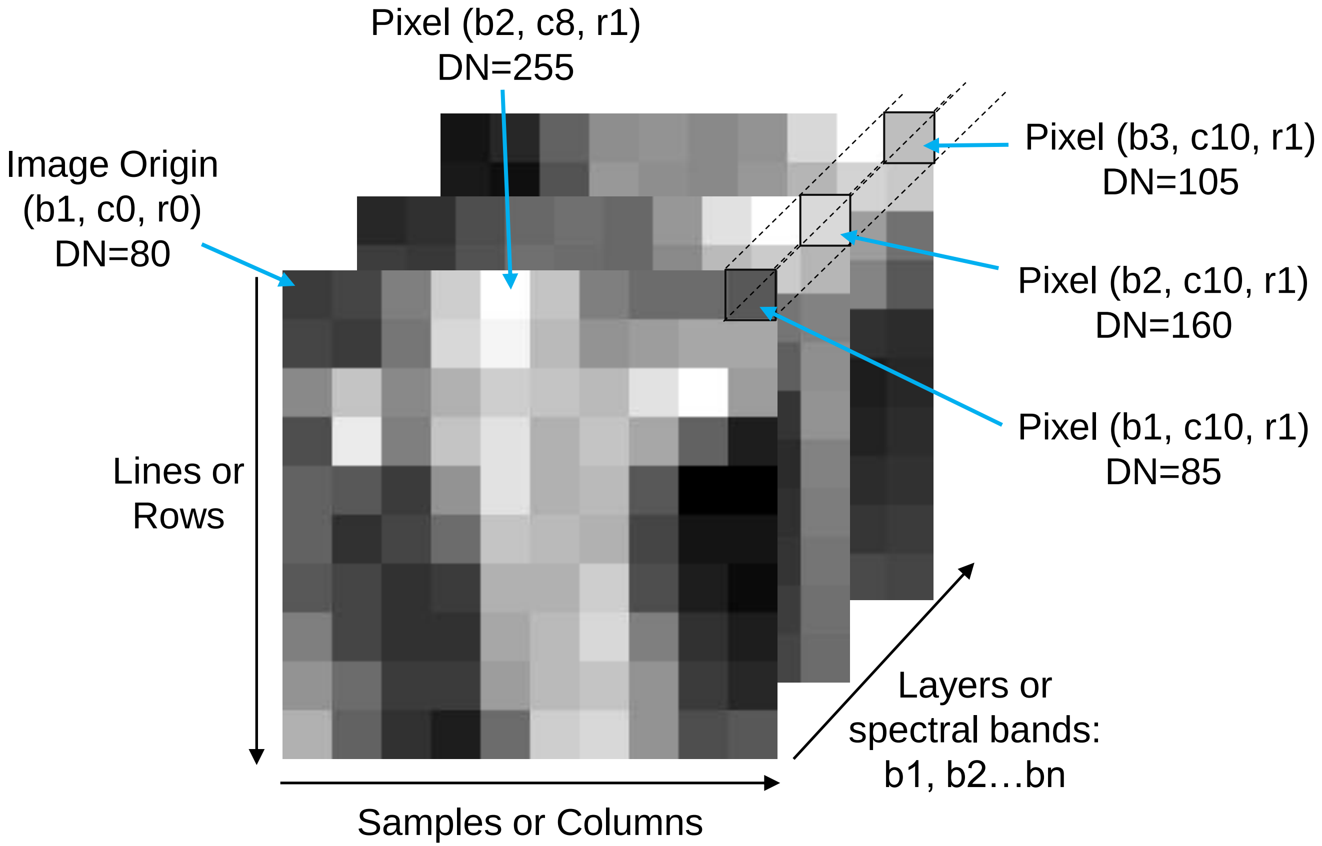
Lecture plan

1. Digital images & monochrome display
2. Tristimulus theory & RGB colour cube
3. Colour composite & pseudocolour display
4. Point operations
5. Common contrast enhancement methods

1.1 Digital image display & point operations

Some revision!

1.1.1 What is a digital image?



A digital, multiband image and its components

= a **two-dimensional (2D) array** of digital numbers in lines and columns (rows and samples) = a **raster dataset**.

(3, 10, 10)

It can also have a 3rd dimension via layers or image bands. Each cell of a digital image is called a **pixel** and the number representing the brightness of the pixel is called a **digital number (DN)**.

A single digital image is **not** a matrix!

But what do these DN represent and what can we do with them?

Brightness in each pixel is a measure of the selective absorption and reflection of electromagnetic radiation from the ground objects within that pixel, at a particular wavelength.

Digital display allows us to visualise reflected/emitted energy at wavelengths beyond the visible range

Chapter 1, Digital image and display, Liu & Mason, Image Processing & GIS for remote sensing, Wiley, 2016

Displaying digital image information

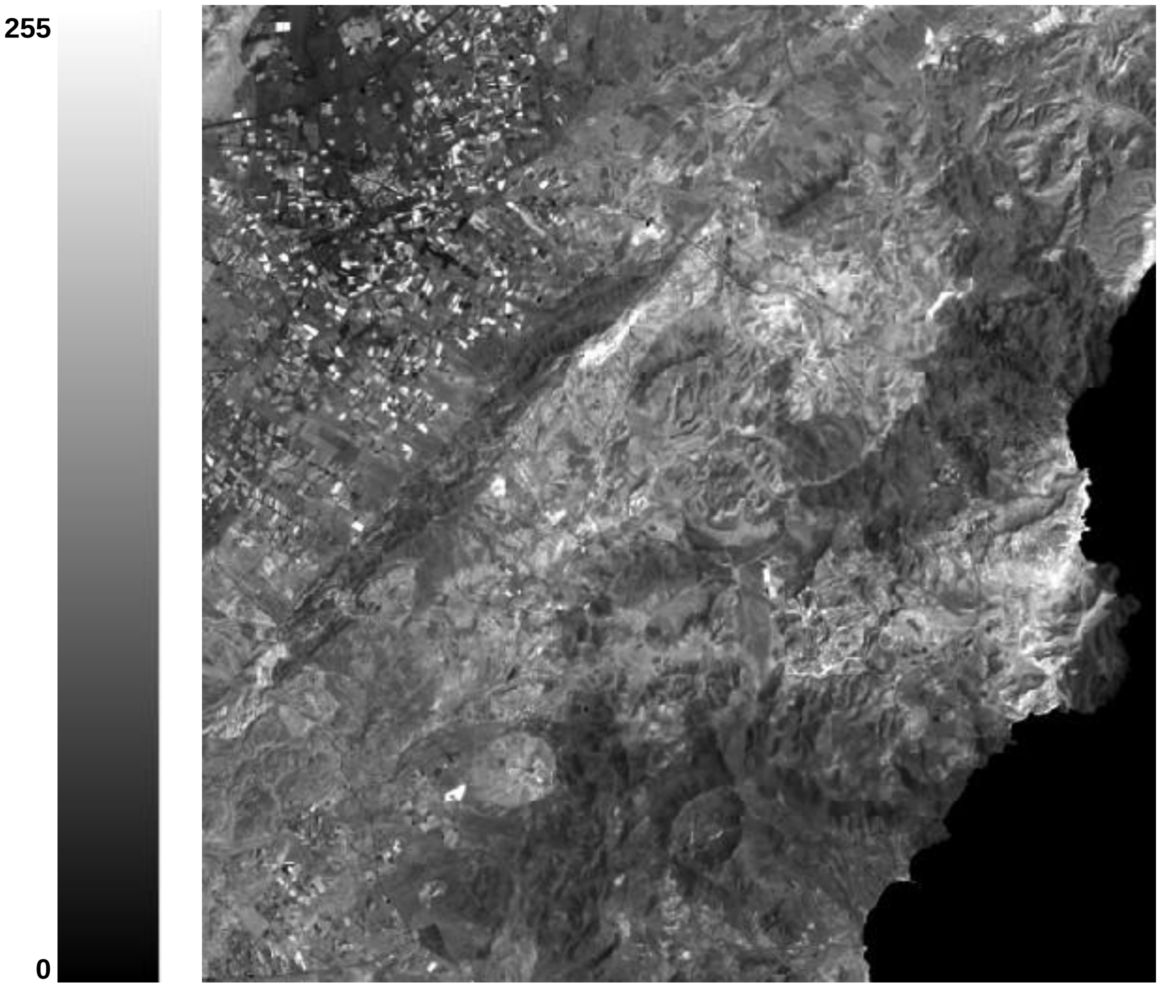
- Colour is the result of **selective absorption and reflection** of electromagnetic radiation (EMR) from an illumination source.
- Human colour perception limited to the Visible spectral range (0.38 - 0.75*μm)*
- Remote sensing technology records reflectance (& emission) across much wider range, as DN values - displayed as either **black/white images** or **colour images** on an electronic display (computer monitor).
- In digital image display, the tones/colours are **visible presentations of relative brightness from the pixel area on the surface (land, water or atmosphere)** recorded as DNs (NB the DNs do not necessarily represent any particular physical meaning … but we can ‘calibrate’ and interpret!)

Major spectral regions used for remote sensing:

Visible light:	*0.4 - 0.7 μm*
Blue (B)	*0.4 - 0.5 μm*
Green (G)	*0.5 - 0.6 μm*
Red (R)	*0.6 - 0.7 μm*
(Visible-photographic IR	*0.5 - 0.9 μm)*
Reflective infrared (IR):	*0.7 - 3.0 μm*
Near Infrared (NIR)	*0.7 - 1.3 μm*
Short wave infrared (SWIR)	*1.3 - 3.0 μm*
Thermal infrared	*3 - 5 μm and 8 - 14 μm*
Microwave	*0.1 - 100 cm*

1.2 Monochromatic image display

- **Any image (<u>panchromatic</u> OR <u>a single spectral band of a multi-spectral image</u>)** can be displayed as a black & white image via a **monochromatic display**.
- Digital display = **conversion of DNs to electronic signals (energy levels)** to generate different grey levels (degrees of brightness) to form the monochromatic image display.



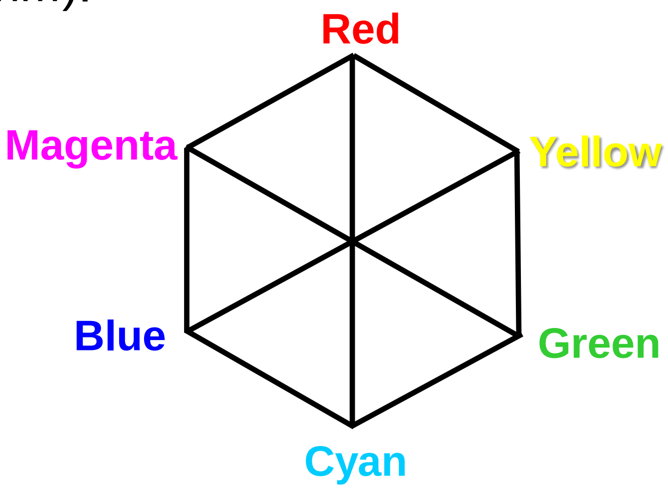
- Most image processing systems support an 8-bit (256 grey levels) display, i.e. DNs range from 0 to 255 (black to white) = wide enough for human visual capacity.
- NB Remotely sensed images may have much wider DN ranges than 8-bits
  - e.g. VHR images (Ikonos, QB, WV), L8 & L9, and Sentinel-2 often have 11-bit DN range, 0 to 2048

Such images can be visualised in an 8-bit display system by compressing the DN range, or by displaying the image in several intervals across the whole DN range.

2.1 Tristimulus colour theory & RGB colour display

Red, green and blue are referred to as **primary colours**.
Human colour perception is performed by three types of cones in the retina with sensitivity peaks matching three primary colours: **R**ed (680 *nm*), **G**reen (545 *nm*) and **B**lue (*440 nm*).

Primary colours and their complementary colours.



A light of non-primary colour (C) **stimulates a different portion of each group of cones** to form the perception of this colour.

Additive mixtures of the primary colour lights can thus produce any colour.

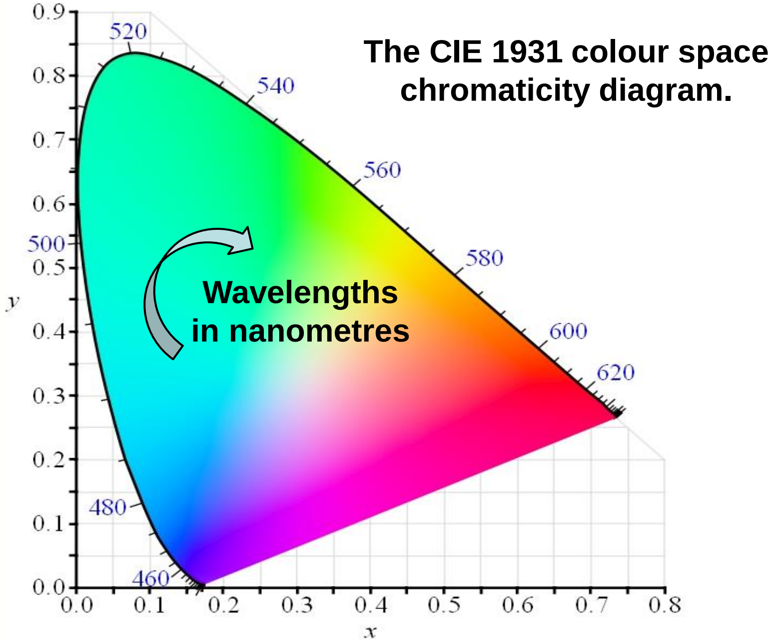
This is the principle of RGB additive colour composition.

$$C = (rR) + (gG) + (bB)$$

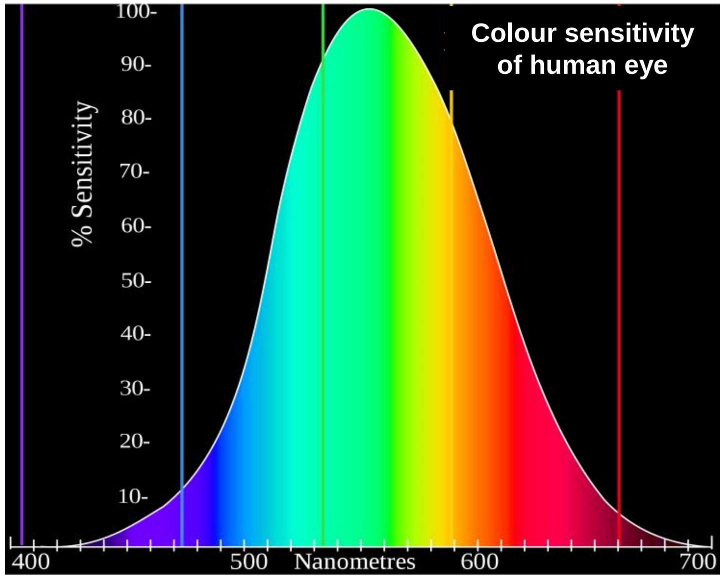
Mixtures of equal amount of three primary colours ($r = g = b$) are **white** or **grey.**

Equal amounts of any two primary colours generates a **complementary colour**: i.e. Yellow, Cyan and Magenta.

[These 3 complementary colours are used as primaries to generate various colours in colour printing.]



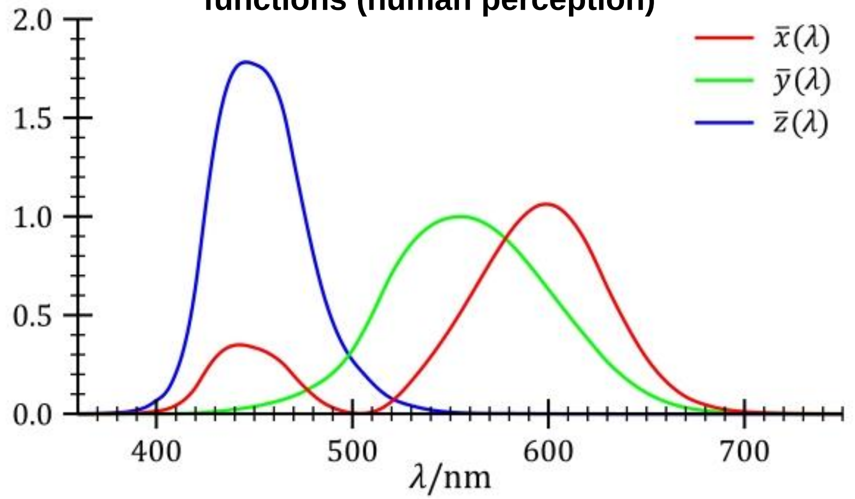
One of the first mathematically defined colour spaces was the CIE (International Commission on Illumination) 1931.



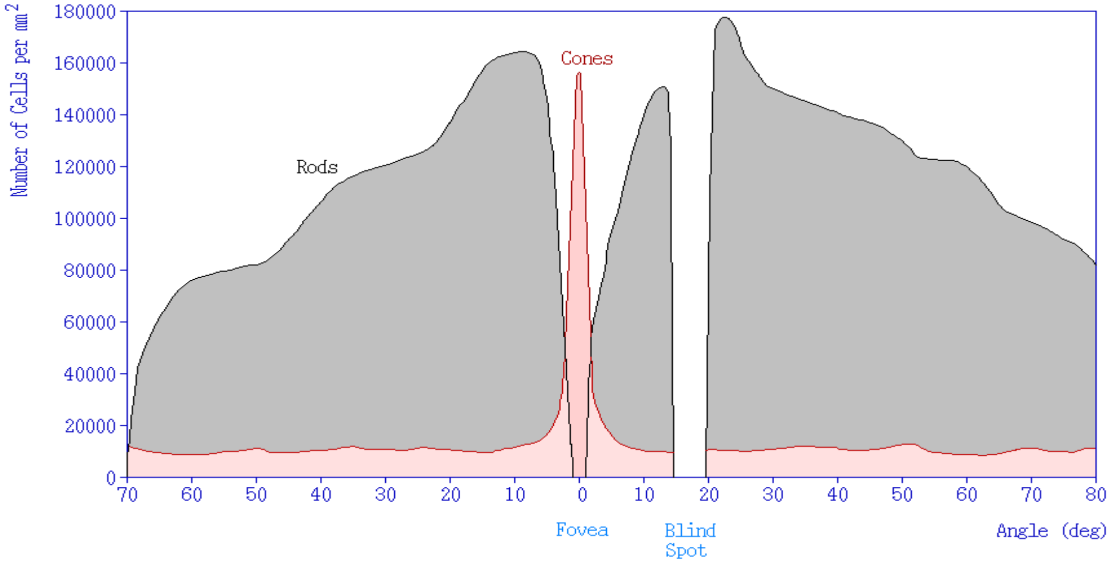
Revision - Tristimulus colour theory and RGB colour display

- An **individual's colour perception depends on the proportion of each of the 3 types of cones stimulated**.
- Thus it be expressed as a **triplet of numbers** (*r, g, b*) even though visible (VIS) light is electromagnetic radiation (EMR) in a continuous spectrum between 400-700 *nm*.
- Digital image colour display is based on the ***tristimulus colour theory***.
- A colour monitor, like a colour TV, contains **3 geometrically registered colour '*guns' light-emitting diodes, or 3 colour filters in a modern liquid crystal display***: red, green and blue. In each '*gun'*, pixels of an image are displayed in reds of differing intensity (e.g. from very dark red to very light red) depending on their digital numbers (DNs).
- Thus if 3 bands of a multi-spectral image are displayed in red, green and blue simultaneously, a colour image display is generated, in which the **colour of a pixel is decided by its variable DNs in red, green and blue bands (*r, g, b*).**
- This is the basis of **Additive RGB Colour Composite System**. In this system, different colours are generated by additive combinations of **R**ed, **G**reen and **B**lue components.

The CIE standard observer colour matching functions (human perception)



Cones present at a low density across the retina, and at high density only in the centre of the fovea.
Rods are present at high density across the retina, at very low density in the fovea – for better perception of overall & peripheral brightness). See below



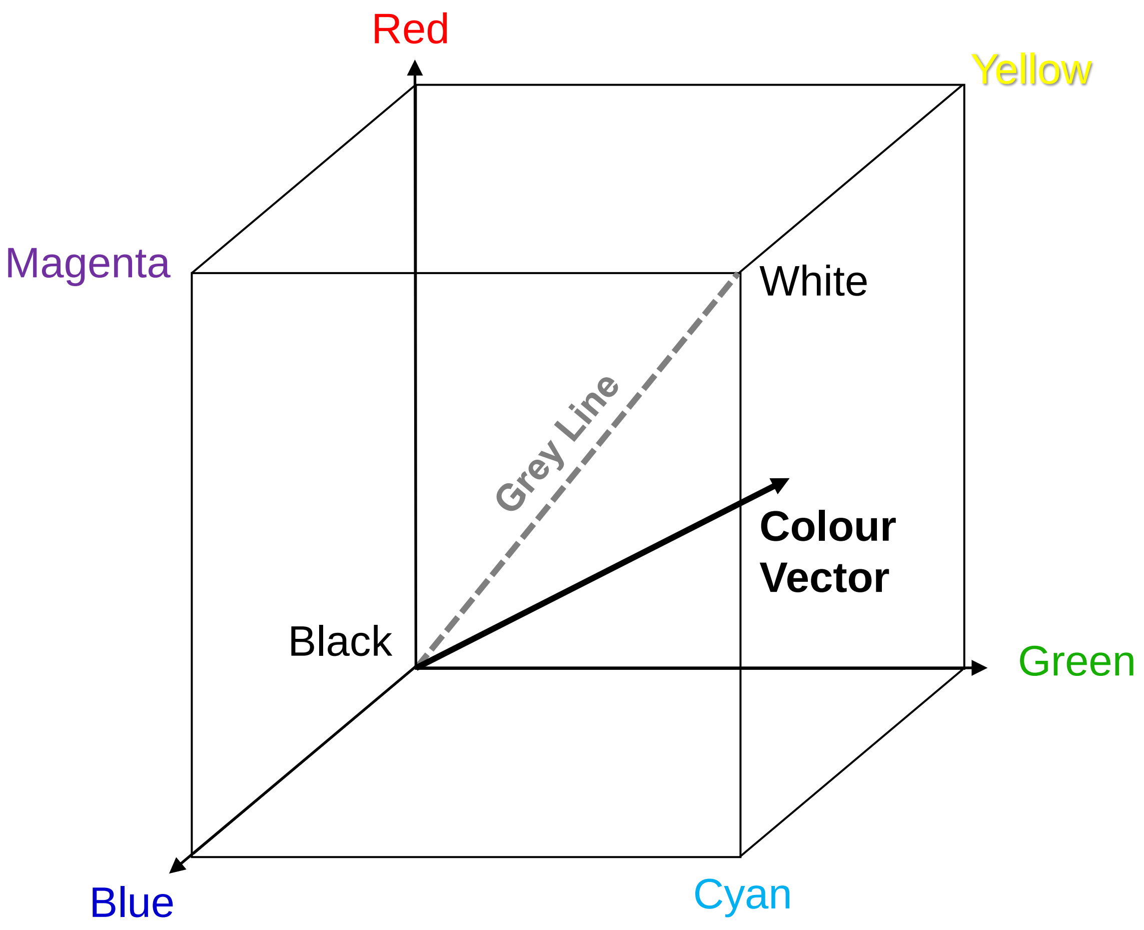
2.2 RGB colour cube and colour composites

Consider the components of an RGB display as the orthogonal axes of a 3D colour space where:

- the max possible DN level in each component of the display defines the **RGB colour cube**.

Any image pixel DN is represented by a vector from the origin to somewhere within the colour cube.

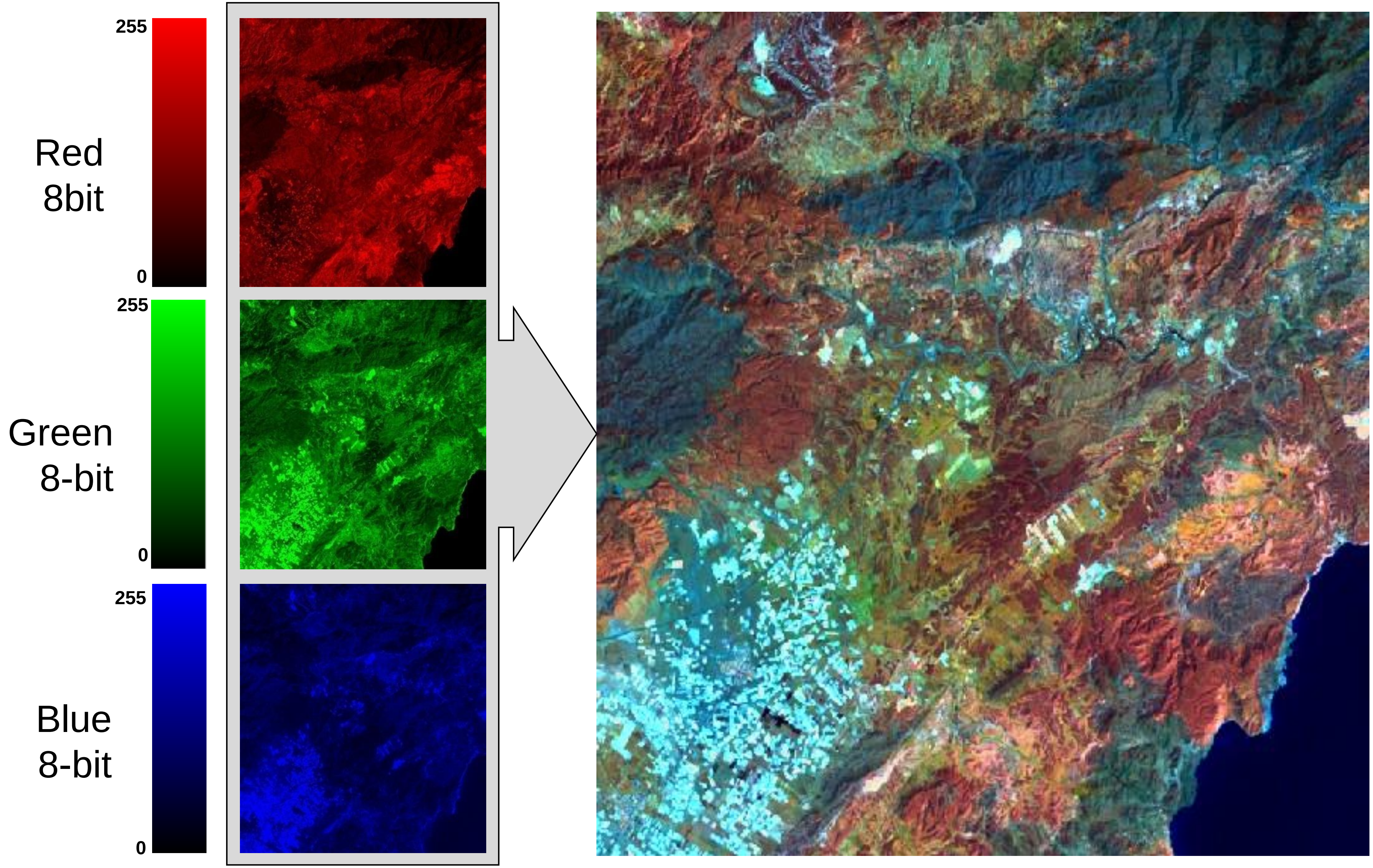
Most standard RGB display system can display 3 x 8-bits/pixel/channel, giving 24-bits (<16.8 million) different colours.



The line from the origin of the colour cube to the opposite convex corner is known as the **grey line** because pixel vectors that lie on this line have equal components in red, green and blue (*i.e.* $\boldsymbol{r} = \boldsymbol{g} = \boldsymbol{b}$).

RGB additive colour image display system

Three monochrome images as input



Output
RGB 24-bit
colour composite

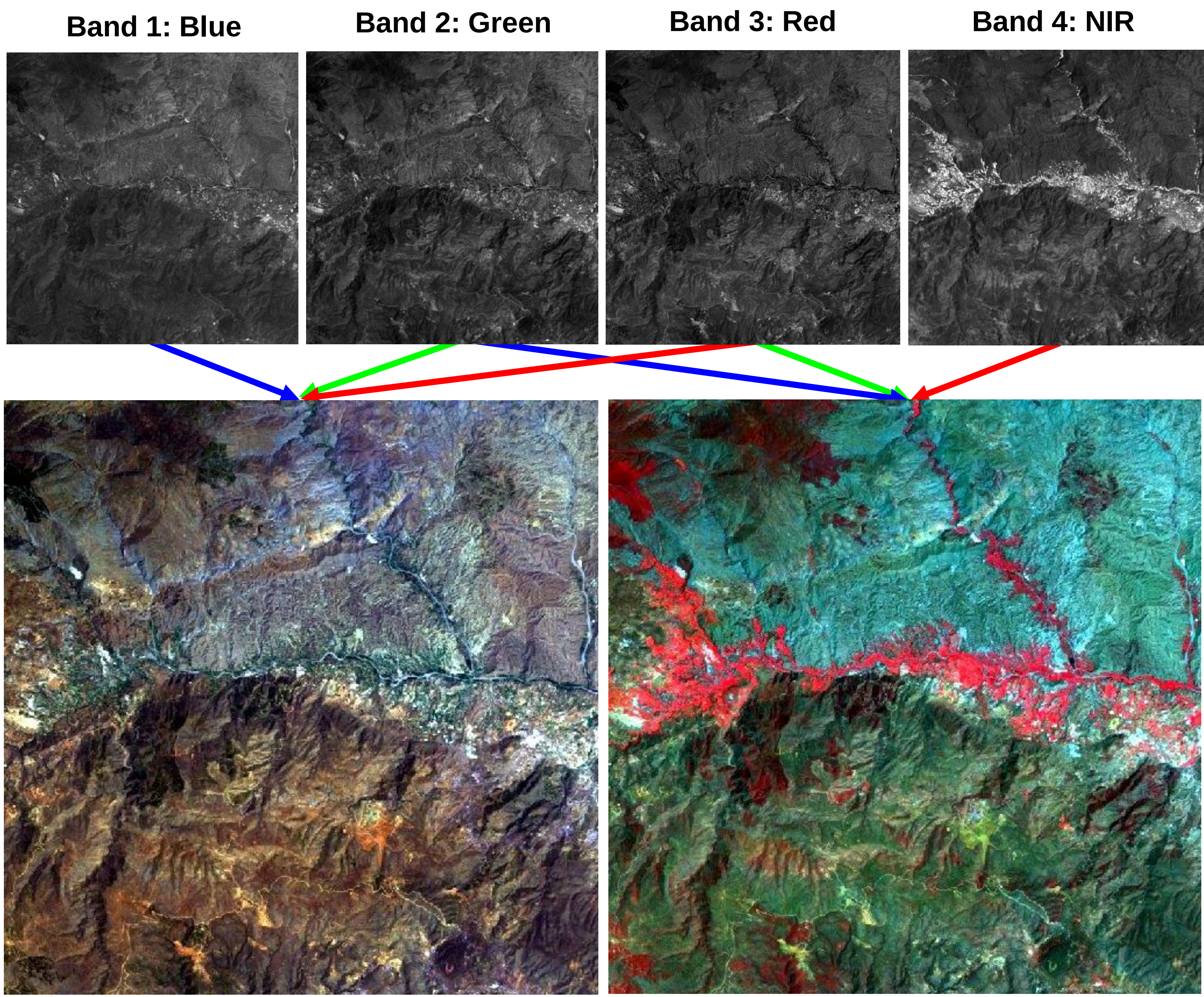
3.1 Colour Composite Display

Although colours we see represent light in the visible spectral range 380-750*nm*, they are also **a tool for visualization**, in colour images

Assignment of each primary colour to a spectral band or layer is arbitrary and but should be done for a purpose:

- Simulated **True colour composite**: 3 spectral bands (Red, Green and Blue spectral ranges) displayed as RGB.
- **False colour composites**: 3 spectral bands (any 3) displayed as RGB.
  - '**Standard false colour composite**': specifically, Near InfraRed (NIR), Red and Green spectral bands displayed as RGB.

The **false colour composite is the general case of RGB colour display** (simulated 'true colour composite' is only a **special case** of it.)



Simulated True Colour Composite

(Standard) False Colour Composite

3.2 Pseudo-colour display

Human eyes recognise far more colours than grey levels - colour may be used more effectively to enhance small brightness differences in a monochrome image.

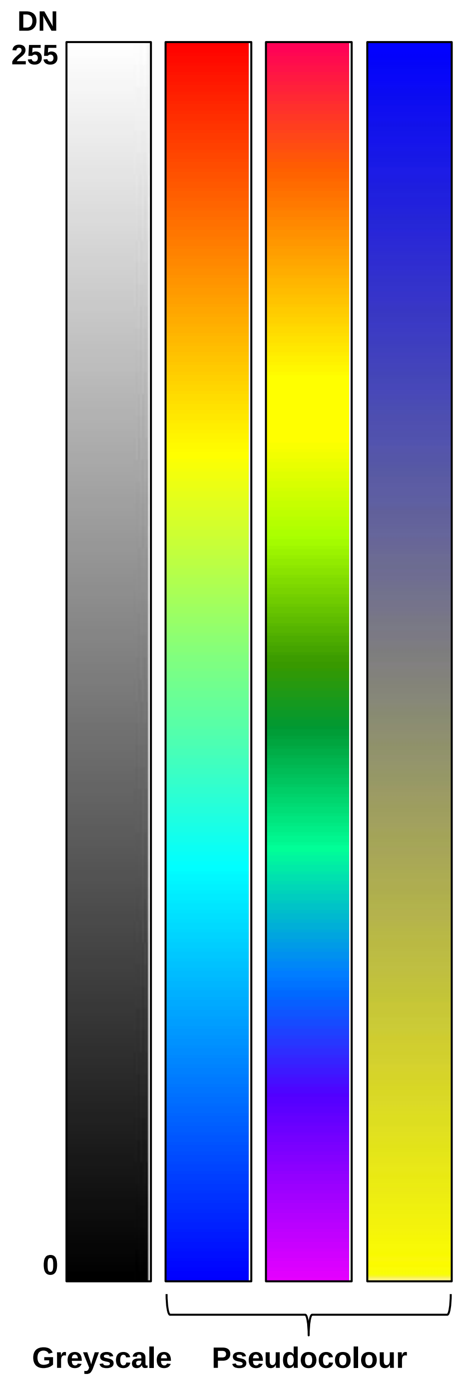
- Display of a monochrome image in colour = '**pseudo-colour' display**.
- A pseudo-colour image is generated by **assigning each grey level to a unique colour.** By interactive colour editing or by graded colour ramps (there are many possibilities).

But this benefit of pseudo-colour display also has a drawback…..

- In a greyscale based with DNs encoded from Black-to-White, the quantitative sequential relationship between different DN values is clear and logical.
- In a pseudo-colour display this crucial sequential information can be lost because the colours assigned to various grey-levels may be not quantitative or sequential, but randomly arranged.

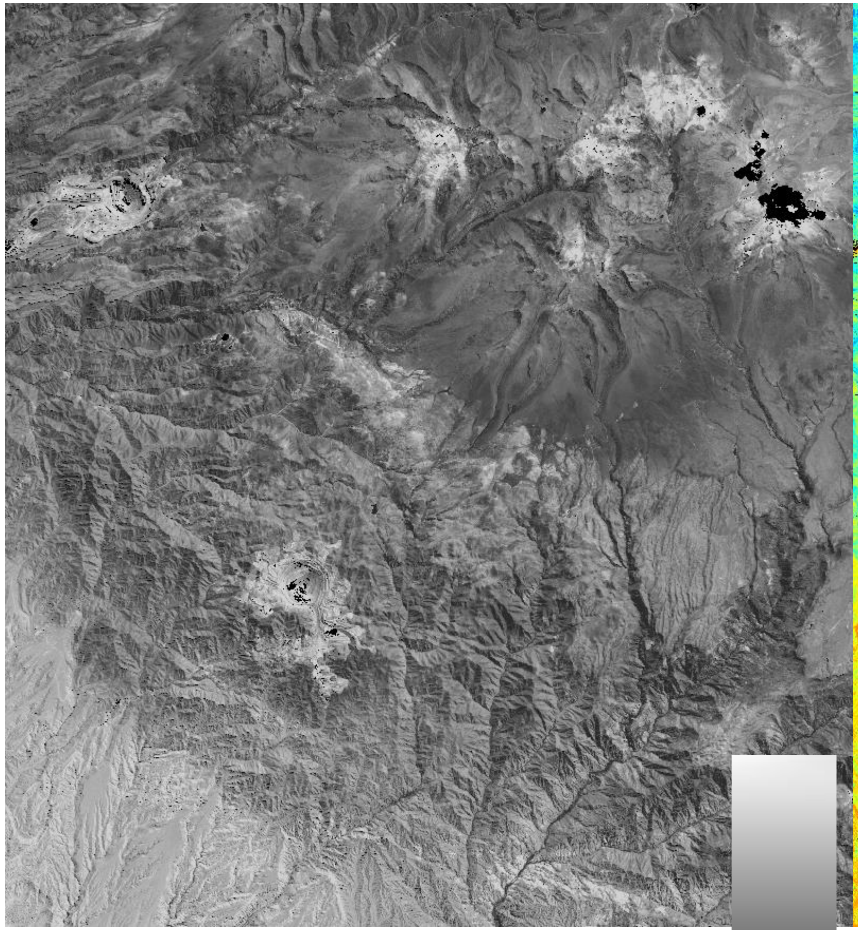
Indeed, an image saved from a pseudo-colour display is an **image of 'symbols**' rather than numbers; it is no longer a true digital image! And the relationship to the original numbers is destroyed.

- **Greyscale B/W display is a special case of pseudo-colour** display where the DN are mapped to a sequential greyscale rather than a colour scheme – so this is always the best way to view a single band image!

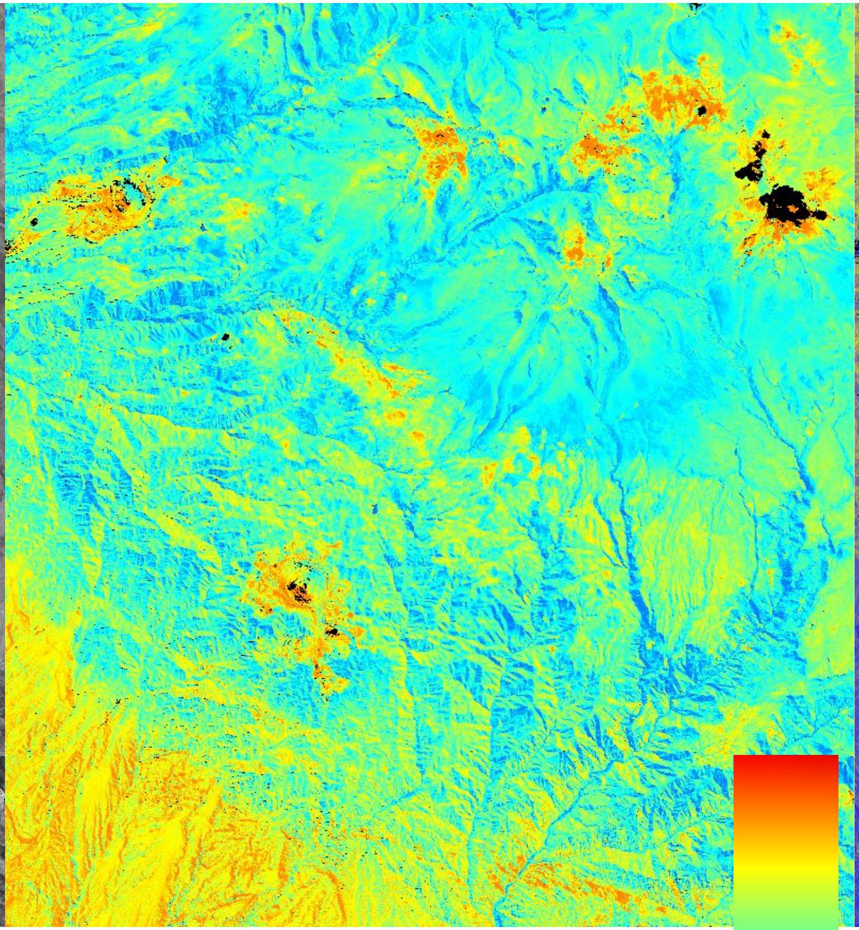


Pseudo-colour display

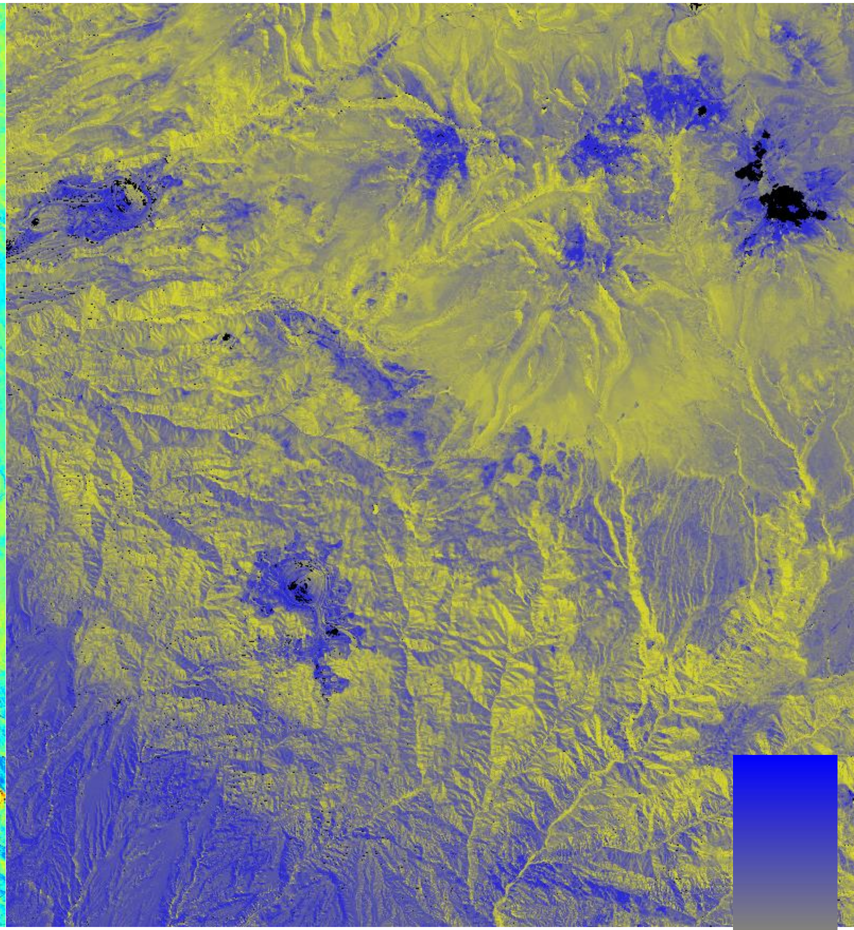
The technique to display a single band monochrome image as a colour image is called **pseudo-colour display**.



Sentinel-2 b3 image in greyscale (B/W) display.



S2 b3 Pseudo-colour (‘rainbow’)



S2 b3 Pseudo-colour ‘Yellow-to-Blue’

4. Point operations (and Contrast enhancement)

- Contrast enhancement, sometimes called ***radiometric enhancement* or *histogram modification***, *etc.*, is the most basic but most effective and efficient technique to optimise the image contrast and brightness for visualization or to highlight information in particular DN ranges.
- Let X represent a digital image and x_{ij} is the DN of a pixel in the image at the i^{th} line and j^{th} column. Let Y represent the output image derived from X by a function f and y_{ij} is the output value corresponding to x_{ij}. Then a contrast enhancement can be expressed in a general form:

$$y_{ij} = f(x_{ij})$$

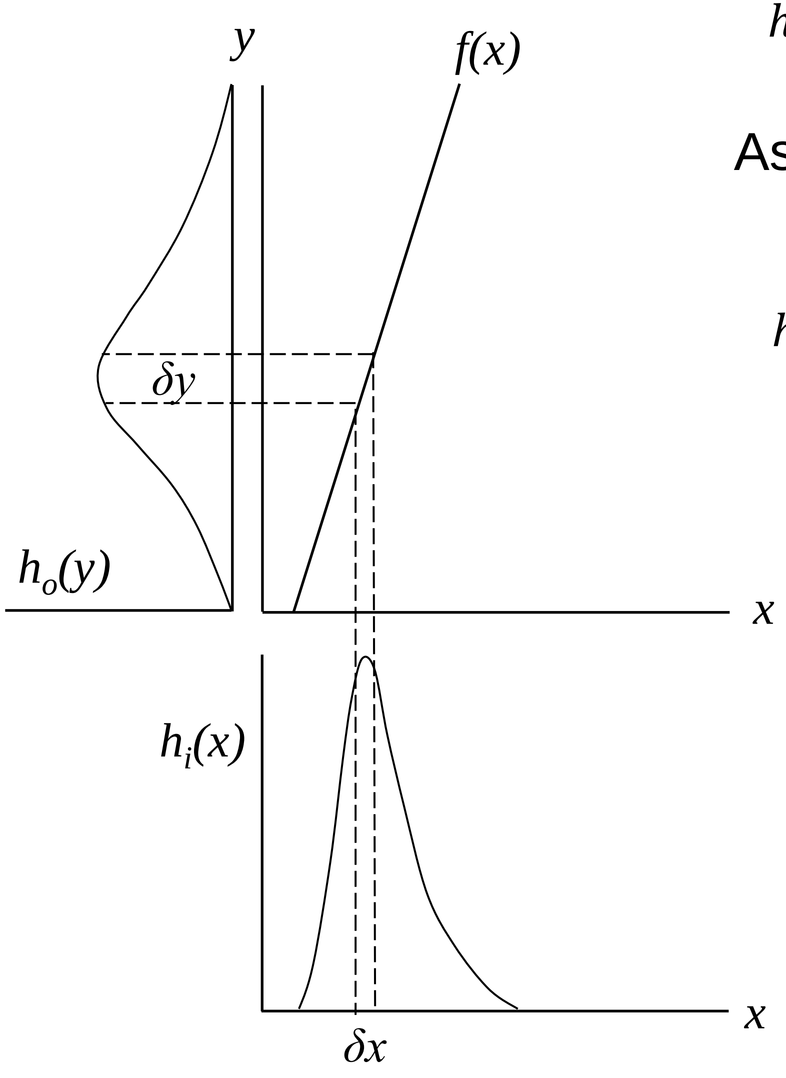
- This transforms a single input image X to a single output image Y, through a function f, such that the DN of an output pixel y_{ij} depends **only on the DN of the corresponding input pixel $\boldsymbol{x_{ij}}$**. This is the essence of a **point operation**.
- Contrast enhancement is a point operation that modifies the image brightness and contrast but does not alter the image size or texture.

Chapter 2, Point operations, Liu & Mason, Image Processing & GIS for remote sensing, Wiley, 2016

4.1 Histogram modification & look up tables (LUT)

- x represents a DN level of an image X, then the number of pixels of each DN level, ***h(x)***, is the **histogram** of image X.
- $h(x)$ is also the % number of pixels of a DN level x against the total number of pixels in image X. So in statistical terms, $h(x)$ is a **probability density function**.
- The histogram presents image **contrast, brightness and data distribution**. Every image has a unique histogram but the reverse is not true – because a histogram contain no spatial information….
- A **histogram modification** can also be called a **point operation because** the operation **only alters the pixel DN values** but not their spatial relationship. For the pixels with the same input DN x, at different locations, the function f will produce the same output DN y. Therefore a point operation can be more concisely defined as:

$$y = f(x)$$



$$h_i(x)\delta x = h_o(y)\delta y$$

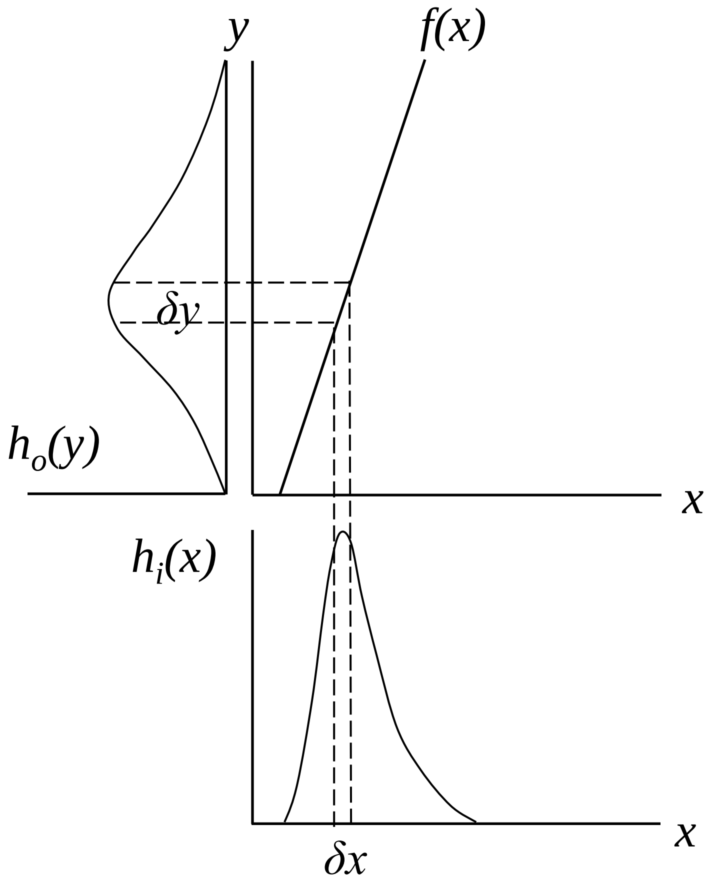
As $\delta x \to 0$ then $\delta y \to 0$

$$h_o(y) = h_i(x)\frac{dx}{dy}$$

$$= h_i(x)\frac{\cancel{dx}}{f'(x)\cancel{dx}}$$

$$= \frac{h_i(x)}{f'(x)}$$

Or $h_o(y) = \dfrac{h_i(x)}{y'}$

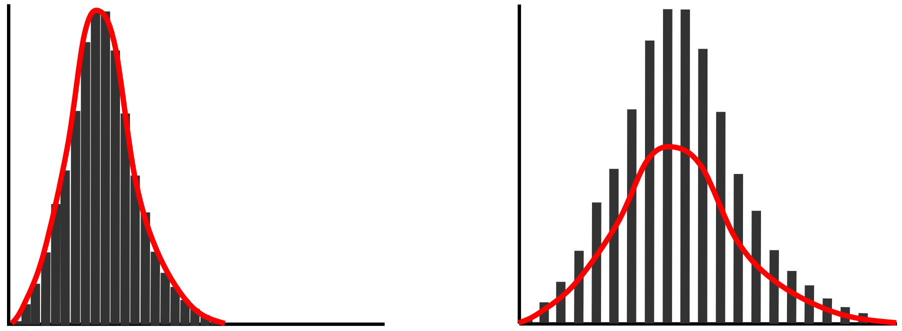


As $f'(x)$ is the gradient of a point operation function $f(x)$, then:

a) when the gradient of a point operation function is **>1**, it is a stretching function which increases the image contrast;

b) when the gradient of a point operation function is **<1** but positive, it is a compressional function which decreases the image contrast.

- A **non-linear** point operation function can **stretch and compress different sections** of DN levels depending on its gradient as shown later in the discussion on logarithmic and exponential point operation functions.
- In the real case of an integer digital image, both $h_i(x)$ and $h_o(y)$ are **discrete functions**. Given a point operation function $y = f(x)$, the DN level x in the image X is converted to a DN level y in output image Y, and the **number of pixels with DN value x in X is equal to that of pixels with DN value y in Y**. Thus,



Before and after linear stretch (for integer image data)

- The point operation modifies the histogram of a digital image by moving the "histogram bar" of each DN level *x* to a new DN level *y* according to the function *f*.
- Though the histogram bars in the histogram of the stretched image (right) are the same height as those in the original histogram (left), the equivalent continuous histogram drawn as a curve is broader and flatter because of the wider interval between these histogram bars.

5. Common contrast enhancement techniques

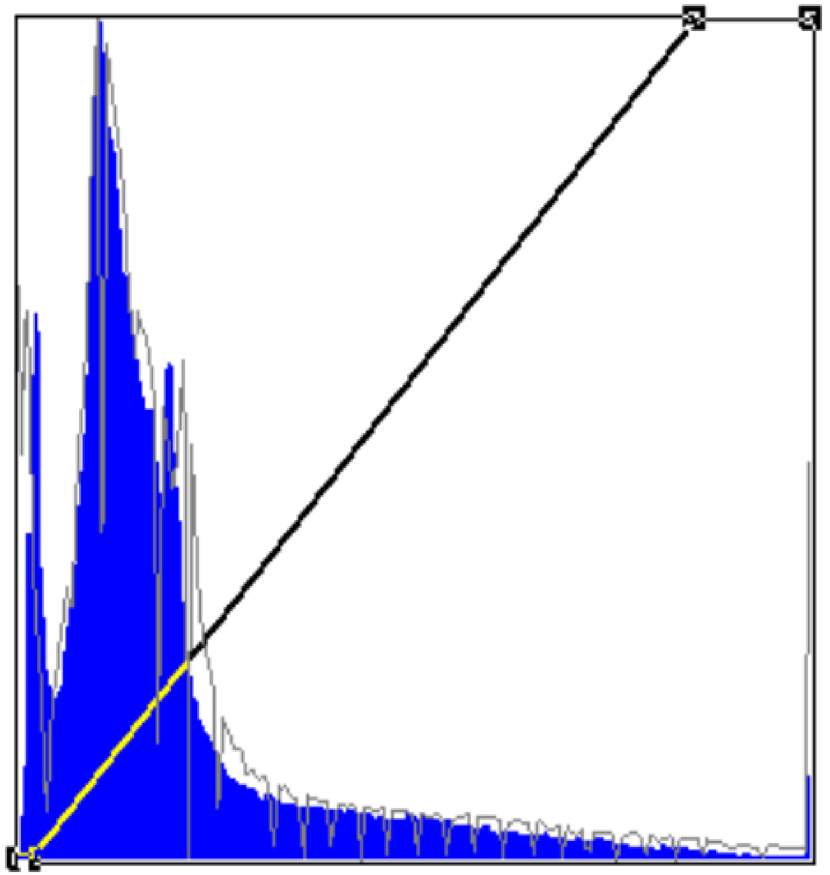
5.1 Linear contrast enhancement (LCE)

$$y = ax + b$$

- LCE is the simplest and one of the most effective contrast enhancement techniques. In this function, a controls the contrast of output images and b modifies the overall brightness.
- LCE improves **image contrast without distorting** the image information **if the output DN range is wider than the input DN range**. In this case, the LCE does nothing but widen the increment of DN levels and shift histogram position along the image DN axis (it does not change the overall shape).

a) Interactive linear stretch

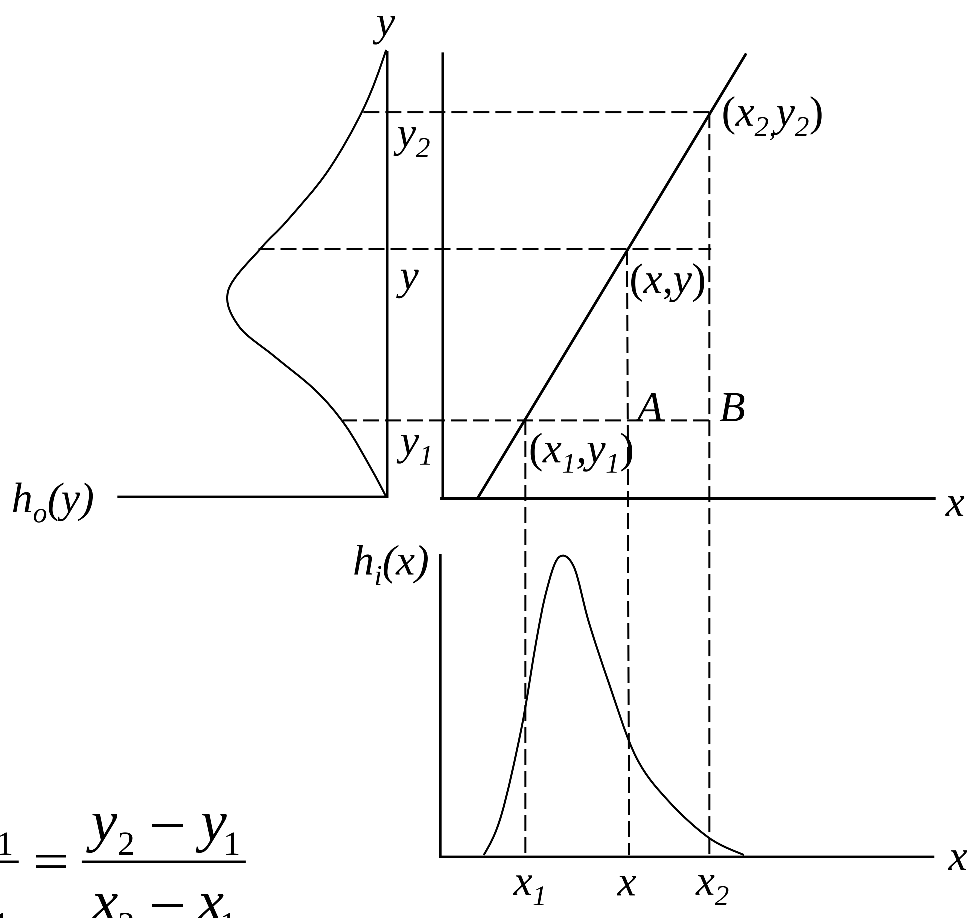
- Changing *a* and *b* interactively allows optimisation of the contrast and brightness of the output image based on user's visual judgement.



b) Automated linear scale

- Automatically scale the DN range of an image to the full dynamic range of a display system (8-bit) based on the **maximum and minimum** of the input image X.

$$y = \frac{255[x - Min(x)]}{[Max(x) - Min(x)]}$$



$$\because \Delta(x,y)(x_1,y_1)A \ \ is\ similar$$
$$to \quad \Delta(x_2,y_2)(x_1,y_1)B$$

$$\therefore \frac{y - y_1}{x - x_1} = \frac{y_2 - y_1}{x_2 - x_1}$$

c) Piecewise linear stretch (PLS)

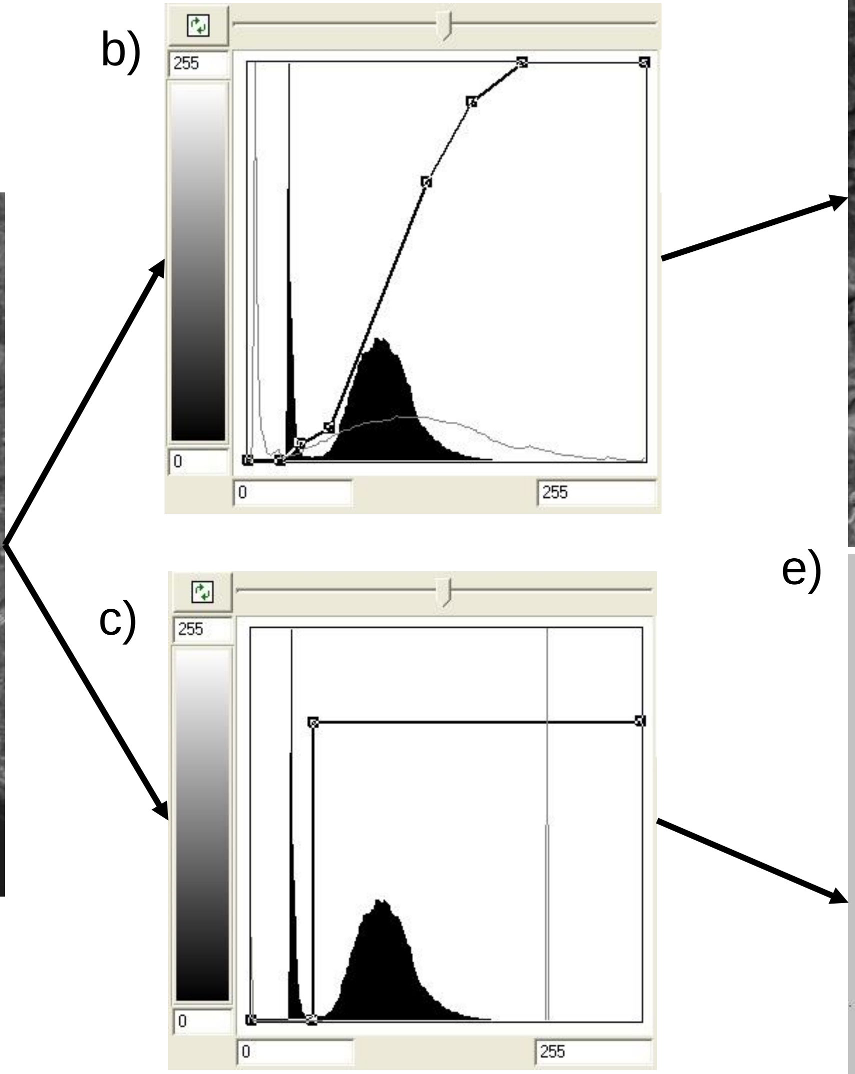
- Use several different linear functions to stretch different DN ranges of an input image. PLS is a very versatile point operation function. It can be used to simulate a non-linear function that cannot be easily defined by a mathematical function.

Interactive PLS function for contrast enhancement and thresholding.

a)

b)

c)

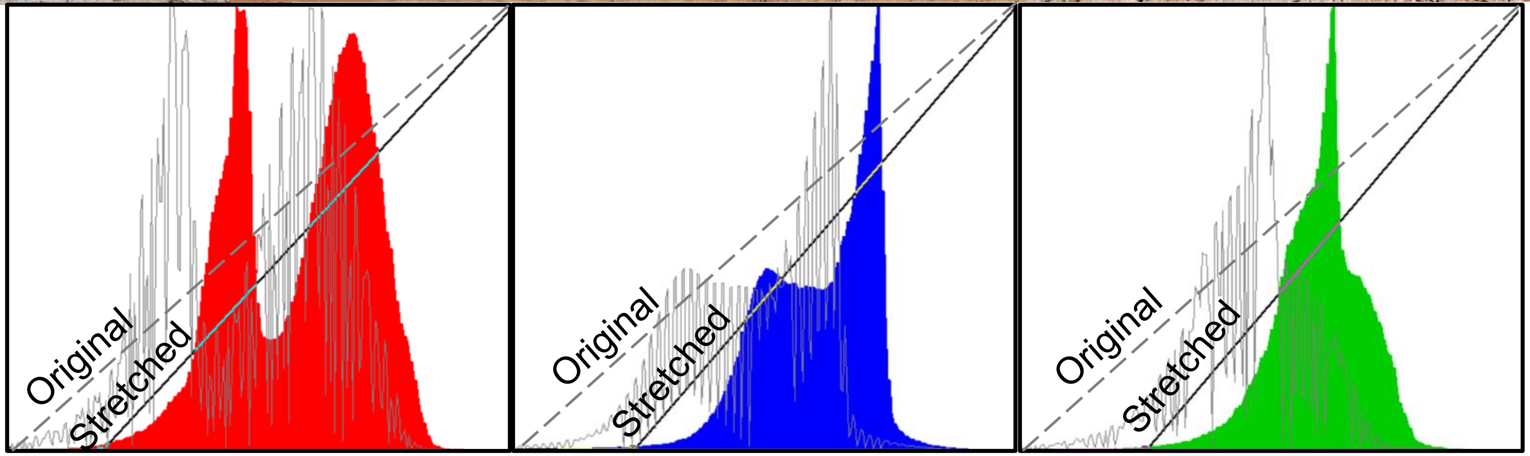


d)

e)

a) Original image; b) PLS function for contrast enhancement; c) Enhanced image; d) PLS function for thresholding; e) Thresholded binary image

A holiday snap with a few rocks!



What is the cause of the pale washed out colours on the left?

How is this correction achieved?

d) Automated clipping for contrast enhancement

- In digital images, a few pixels (often representing noise) may occupy wide value range at the low and high ends of histograms.
- In this case, setting a careful % cut-off to clip the both ends of the histogram is necessary in contrast enhancement to make an effective usage of the dynamic range of a display device.
- Clipping is often given as a percentage of total number of pixels in an image.
- For instance, if you set 1% and 99% as the cut-off limits at the low and high ends of the histogram of an image, the image is then stretched to produce an output image which has
    - DN levels $<x_l$, where $H_i(x_l) = 1\%$, set to 0 and
    - DN levels $>x_h$, where $H_i(x_h) = 99\%$, set to 255

  (for a 8 bits/pixel/channel display).

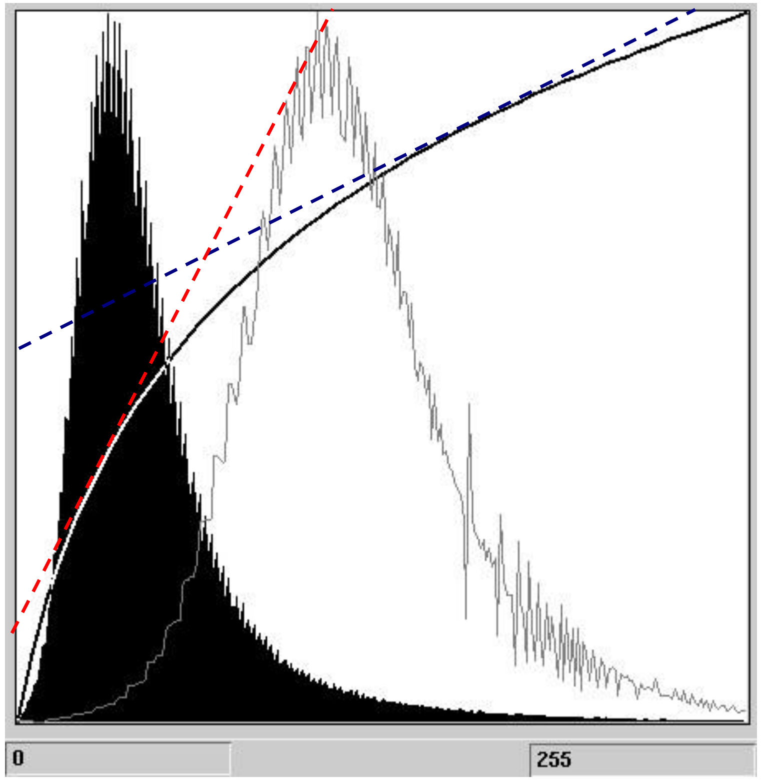
5.2 Logarithmic & Exponential CE

- Logarithmic and exponential functions are the inverse of one another.
- For contrast enhancement, the two functions modify image histograms in opposite ways. **Both functions change the shapes of image histograms and therefore distort the original image information**.

a) Logarithmic contrast enhancement

$$y = b\ln(ax + 1)$$

$y' > 1$ $y' < 1$



Here a controls the curvature of the logarithmic function while b is a scaling factor to make the output DNs within a given value range, and the shift (+1) is to avoid the zero value at which the logarithmic function loses meaning.

The gradient of the function is >1 in the low DN range thus

- Expands low DN values

and at the high DN range, the gradient of the function is < 1, thus

- Compresses high DN values.

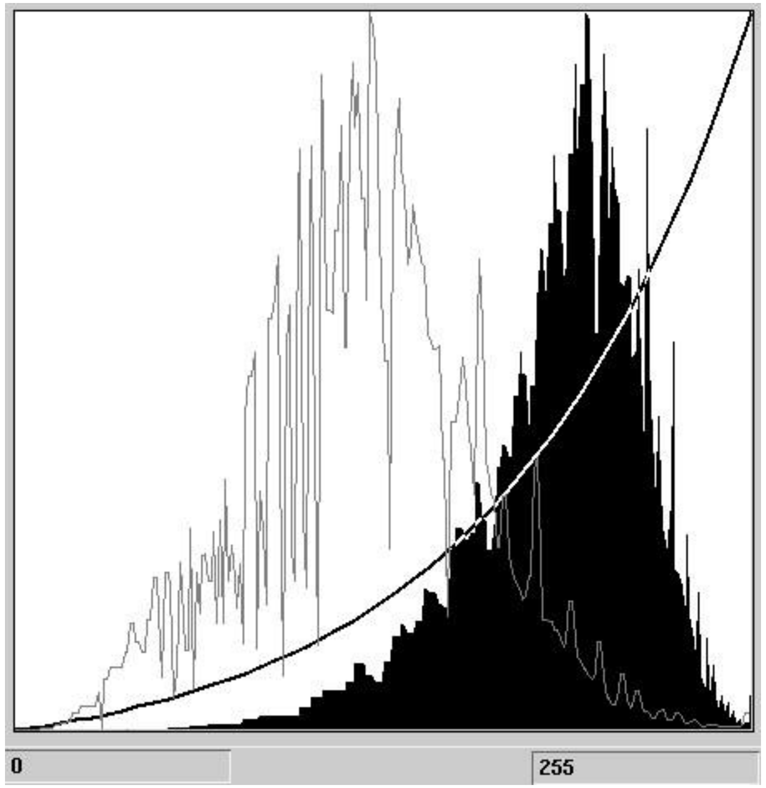
As a result, logarithmic contrast enhancement shifts the peak of image histogram to the **right** and enhances the details in dark areas of an input image.

Many images have histograms in a form similar to logarithmic normal distribution. In this case, a logarithmic function will modify such a histogram into a shape of normal distribution.

b) Exponential contrast enhancement

Here a controls the curvature of the exponential function while b is a scaling factor to make the output DNs within a given value range and the exponential shift (+1) is again to avoid the zero value because $e^0 = 1$

$$y = b\,\mathrm{e}^{ax+1}$$



As the inverse of the logarithmic function, exponential contrast enhancement shifts the image histogram peak to the **left** by expanding high DN values and compressing low DN values

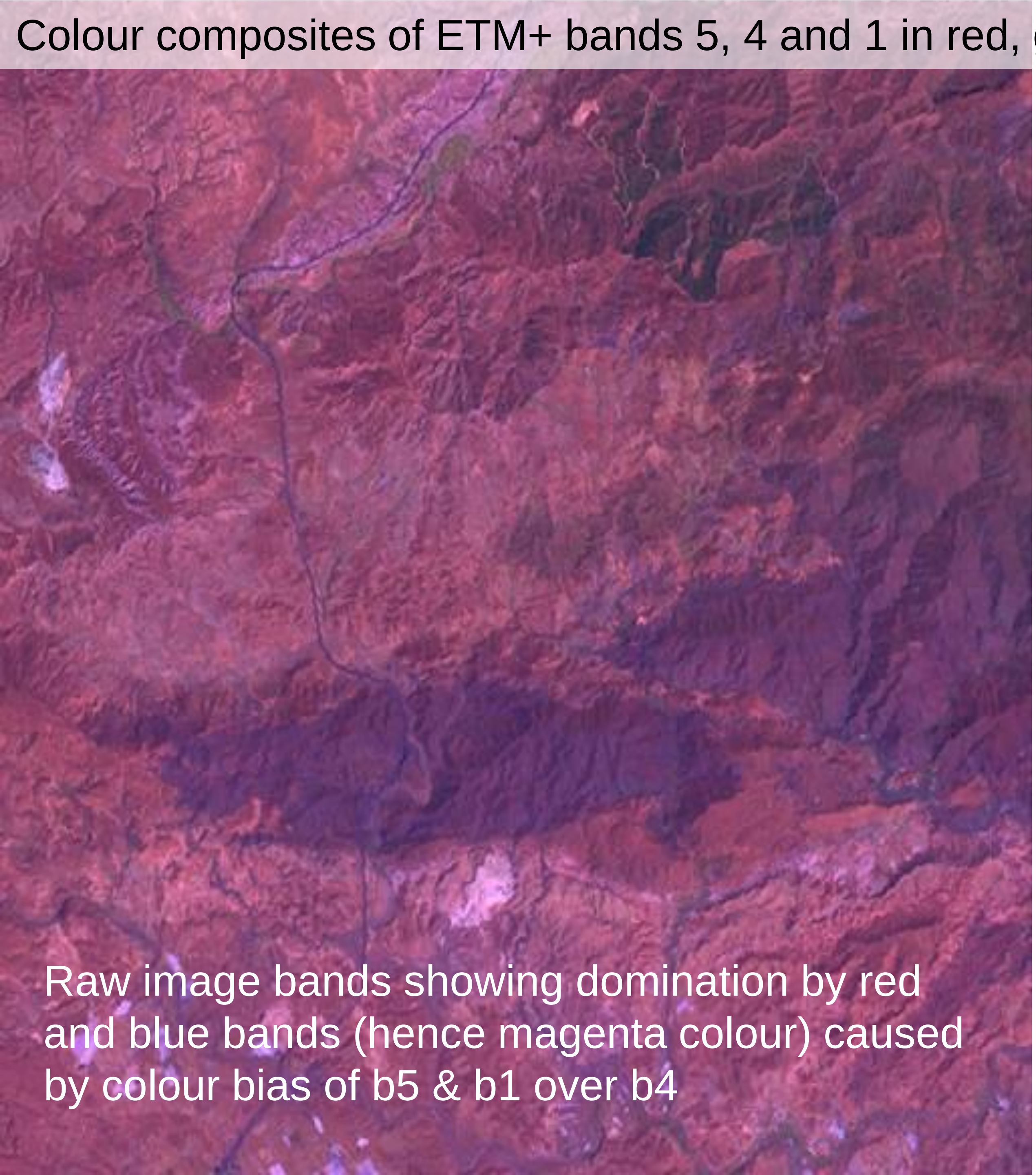
This enhances image details in bright areas at the cost of suppressing the tone variation in dark areas as illustrated in the figure on the right.

Other contrast enhancement techniques

- Histogram equalisation & Histogram matching
- Gaussian stretch

All distort the image information significantly and should not be used if the actual DN values and their relationships to one another are important

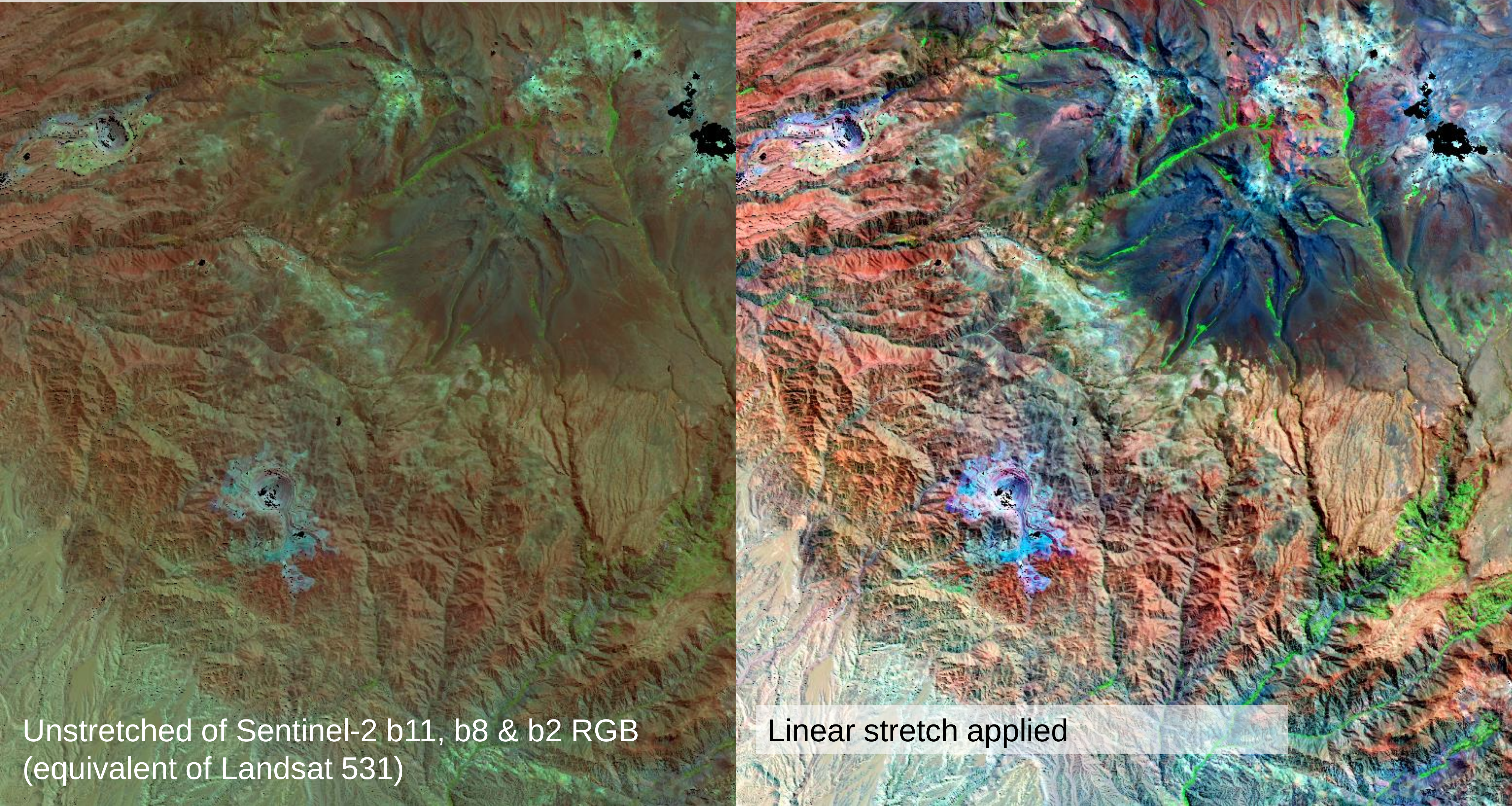
Colour composites of ETM+ bands 5, 4 and 1 in red, green and blue:



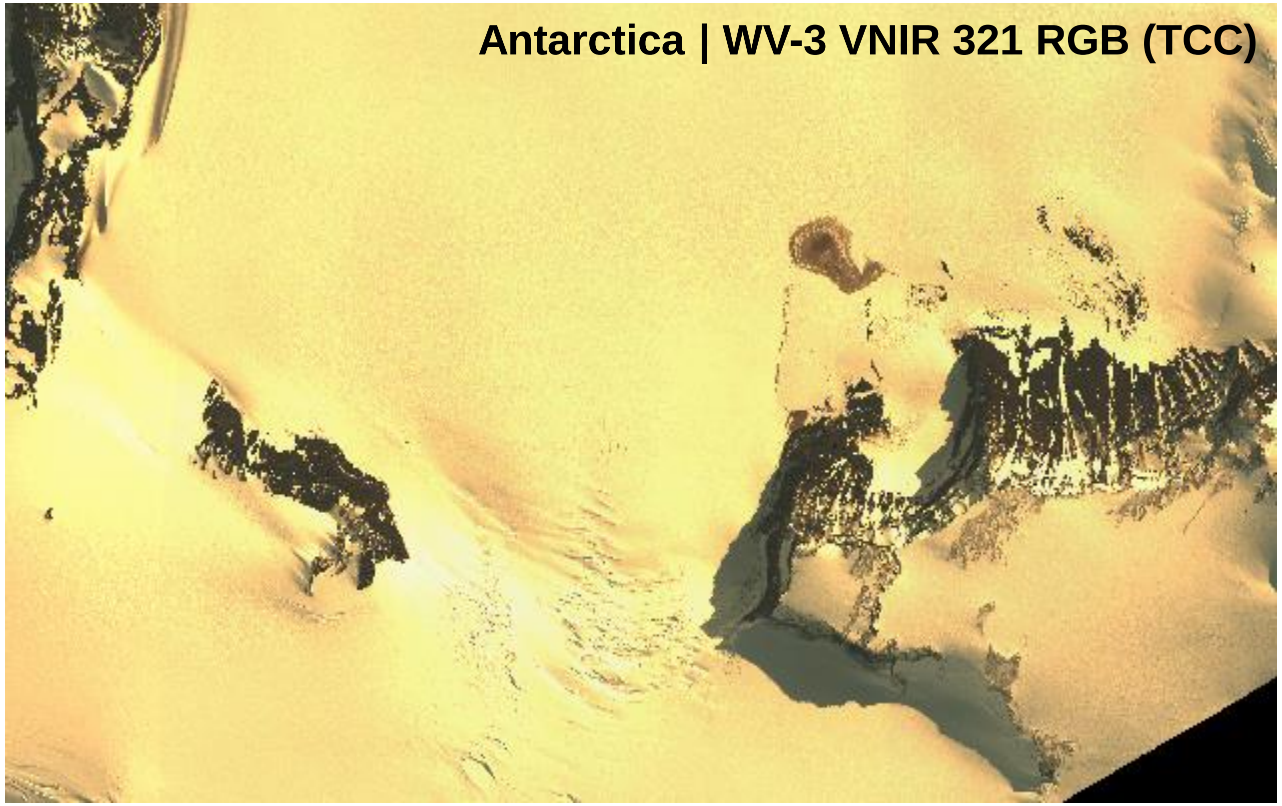
Raw image bands showing domination by red and blue bands (hence magenta colour) caused by colour bias of b5 & b1 over b4

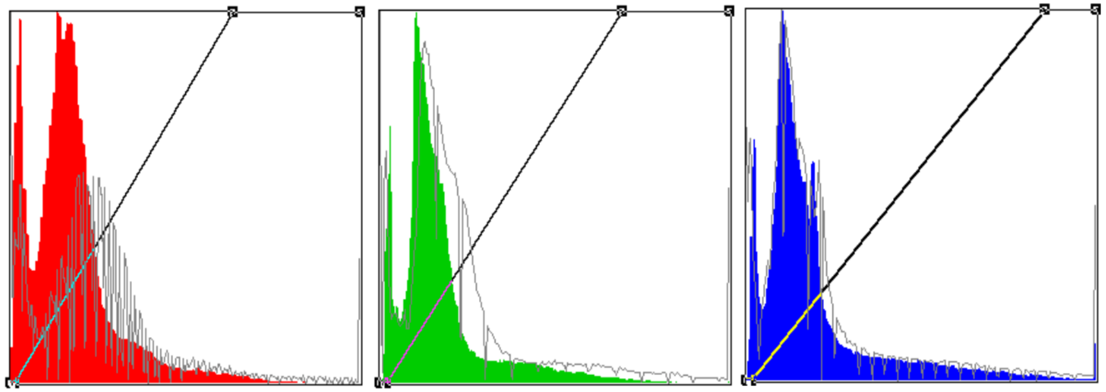
After stretch is applied to all bands: providing an equal value range of 0-255 and mean of 110 in each band

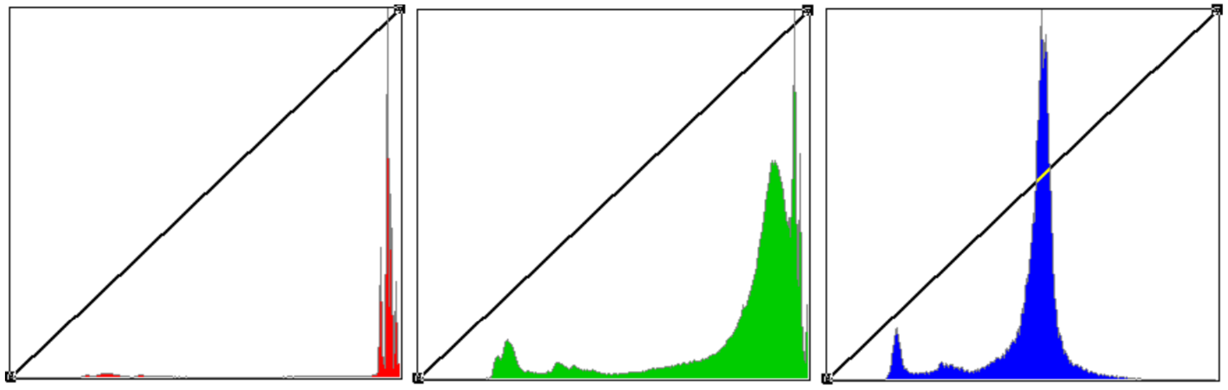
Colour composites of ETM+ bands 5, 4 and 1 in red, green and blue:



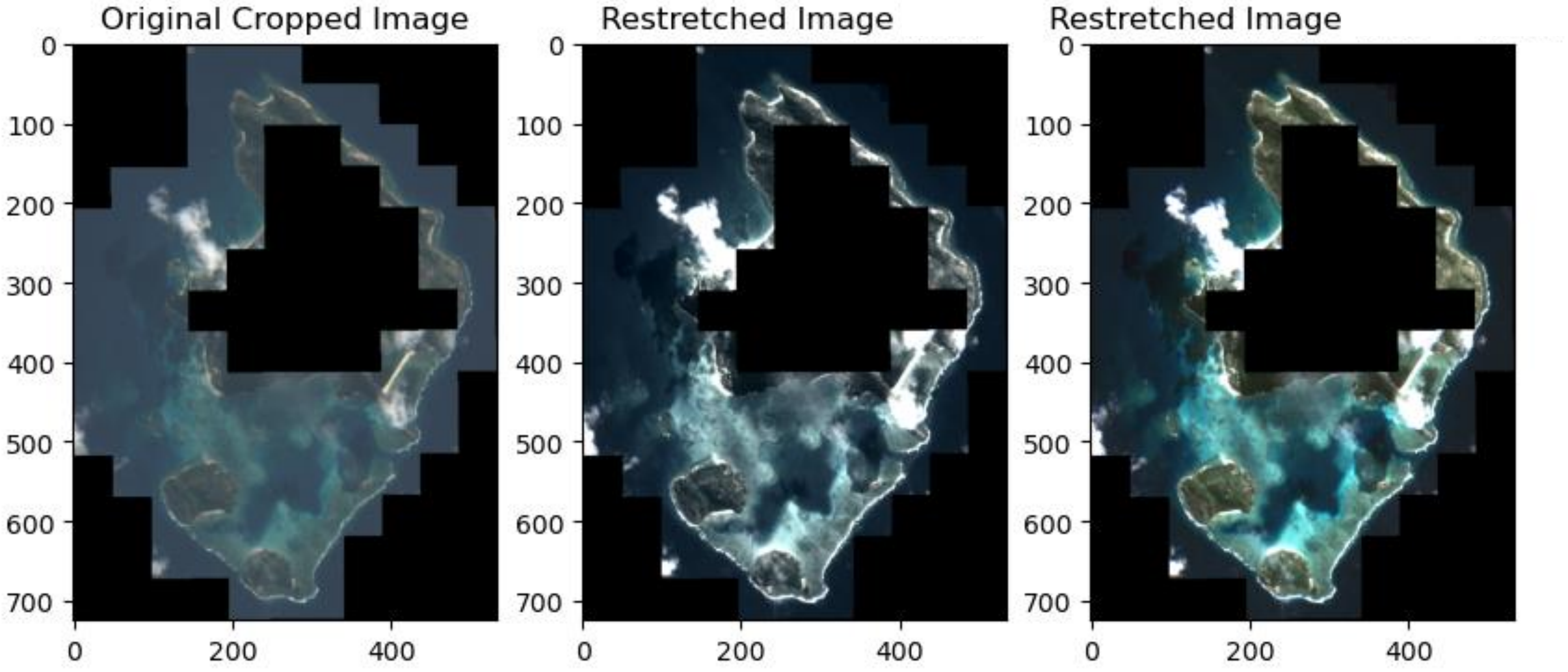
Tricky situations where most CE techniques fail to improve the image ……. Why?







Tricky situations where most CE techniques fail to improve the image ……. Why?



A word about EO data formats in the 21st century

NASA Earth Data processing levels

Data level	Description
Level 0	Unprocessed instrument data (radiance) at full resolution with artefacts removed
Level 1A (L1A)	Unprocessed instrument data at full resolution with radiometric and geometric corrections applied
Level 1B (L1B)	L1A data processed to sensor units (**radiance**)
Level 1C (L1C)	L1B data including new variables to describe the spectra. Often terrain corrected (orthorectified) - L1T
Level 2A	Derived geophysical variables at the same resolution as L1
Level 2B	**Surface reflectance**

ESA (Sentinel-2) Earth Data processing levels

Data level	Description
Level 0	Raw measured data (radiance) at full resolution
Level 1A (L1A)	Unprocessed instrument data at full resolution. Product not available to public
Level 1B (L1B)	Data corrected for dark signal, crosstalk, defective pixels and de-noised **radiance**. Product not available to public
Level 1C (L1C)	L1B data corrected for radiometric and geometric effects, orthorectified and spatially referenced. Top of atmosphere (TOA) reflectance
Level 2A	Statistically classified data with atmospheric corrections to derive Bottom of atmosphere (BOA) **surface reflectance** products.

Raw

Apparent Reflectance

But beware automated correction to L2 reflectance products!

5.4 Tips for interactive contrast enhancement

- The general purpose of contrast enhancement is to optimise visualization.
- Usually after quite complicated image processing, you still need to apply interactive contrast enhancement to view the results properly.
- After all, **an image is designed to allow you to see the information**.
- Visual observation is always the best way to judge image quality. Although this is seems rather non technical, it is a golden rule and is always very true!
- The histogram is the most effect guide to improving an image’s visual quality and the following guidelines for histogram modification may be useful:

Golden rules:

1. **Make full use of the dynamic range of the display system**. This can be done by specifying the actually limits of the input image to 0 and 255 for an 8-bit display. Here percentage clipping is useful to avoid large gaps at the two ends of the histogram.
2. **For optimum visualisation, the histogram peak should lie near the centre of the display range**. For most images, the peak can often be slightly skewed toward the left to achieve the best visualization (unless the image is dominated by bright features in which case the peak could skew toward right).
3. **A point operation function modifies an image histogram according to the function's gradient or slope:**

    If gradient =1 (slope = 45°), the function does nothing

    If gradient >1 (slope > 45°), the function stretches

    If gradient <1 (slope < 45°), the function compress

    Therefore it is a common approach to use functions with slope >45° to spread peak section and those with slope <45° to compress the tails at the both ends of the histogram.

Working with Earth Observation data using open-source python tools

Make a working environment for your raster processing
You will need to install the following packages (e.g. from conda or conda-forge) since they will be used often:

- **rasterio** Reads and writes geospatial raster datasets
- **matplotlib** Publication quality figures, images, plots etc
- **pandas** Data structures for data analysis, time series, and statistics
- **geopandas** Geographic pandas extensions, includes projection between coordinate systems
- **shapely** Manipulation and analysis of planar geometric objects. Uses o-s geometry library GEOS
- **folium** For visualising geospatial data
- **gdal (or libgdal)** Translator library for geospatial data formats (published by Open Source Geospatial Foundation)

- **earthpy** Utility functions for the working with spatial data in the Earthpy tutorial set

Installing these may take some time!!

And for all kinds of ML clustering and classification, there is also Scikit-learn