EART97051 Environmental Data (EDSML) - Earth Observation & Remote Sensing

4 Colour coordinate transformations and their applications

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Lecture plan

RGB-HSI coordinate transformations & applications

1. Definition of HSI & converting from RGB
2. Decorrelation Stretch methods
    - HSIDS and DDS
3. RGB-HSI for data fusion & methods
4. Alternative data fusion method (SFIM)
5. Summary & revision questions

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3. Colour coordinate transformations & applications

3.1 RGB-HSI transformation

A colour is expressed as a composite of three primaries: Red, Green and Blue, according to tristimulus theory. For RGB additive colour display of digital images, a simple RGB colour cube is the most appropriate model.

But for colour perception, a colour is more intuitively and more quantitatively described in terms of three variables.

- **H**ue: colour spectral range
- **S**aturation: colour purity
- **I**ntensity: colour brightness (energy level)

The RGB-HSI colour coordinate transformation within a colour cube is similar to a transformation from three-dimensional Cartesian to Conical (or 3D polar) coordinates.

We can exploit this relationship between RGB and HSI with two key benefits:

1. **Decorrelation Stretch** – for image spectral enhancement (2 common methods)
2. **Data fusion** – for sharpening image texture (3 common methods)

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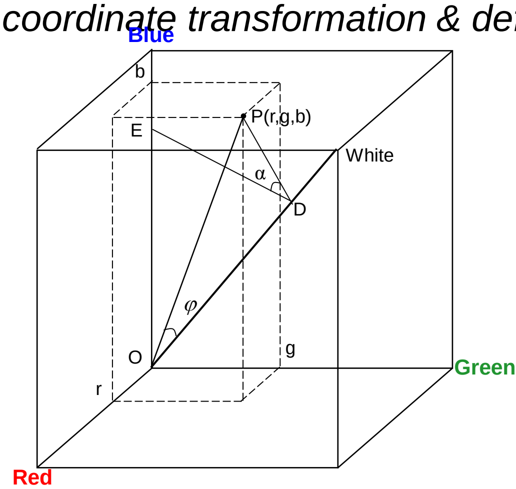
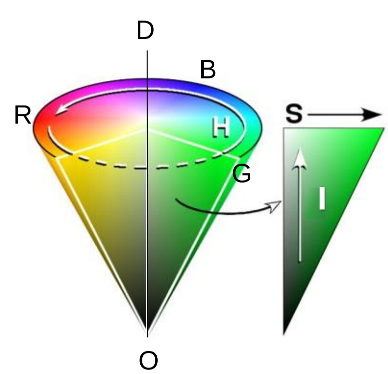
Colour coordinate transformation & definition of H, S & I





- Any colour in a 3-band colour composite is a vector $\mathbf{P}(r,g,b)$ within a colour cube with edge length of 255 (for 24 bits RGB colour display).
- The major diagonal line connecting the origin and the furthest vertex is called **grey line**.
- Intensity of a colour vector P is defined as the length of its projection on the grey line (*OD)*,
- The hue is the azimuth angle around the grey line (α), and
- The saturation is the angle between the colour vector P and the grey line (φ).

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RGB-HSI colour coordinate transformation is based on the colour cube:

		Value ranges
Intensity	$I(r,g,b) = \frac{1}{\sqrt{3}}(r+g+b)$	0 - 255
Hue	$H(r,g,b) = \arccos\frac{2b-g-r}{2V}$ $where \quad V = \sqrt{(r^2+g^2+b^2)-(rg+rb+gb)}$	0 – 2π or 0 - 360 deg
Saturation	$S(r,g,b) = \arccos\frac{r+g+b}{\sqrt{3(r^2+g^2+b^2)}}$	0 - 1

$$\boxed{S(r,g,b) = \frac{Max(r,g,b) - Min(r,g,b)}{Max(r,g,b)}}$$

The greater difference between min & max, the more saturated the colour

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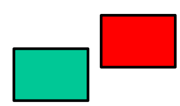
The last formula for saturation implies that a colour vector reaches full saturation if at least one of its *r, g* and *b* components is equal to 0, while not all of them are 0.

For instance, colour P(r, g, b) = (255, 0, 0) is pure red with full saturation and P(r, g, b)=(0, 200, 150) is a greenish cyan with full saturation.



So, what is the HSI-RGB transformation?

Given intensity I, hue angle α and saturation angle φ, we can also derive the HSI-RGB transformation, trigonometrically, using the same 3D polar geometry depicted in the colour cube:

$$B(\alpha,\varphi,I) = \frac{I}{\sqrt{3}}(1+\sqrt{2}\tan\phi\cos\alpha)$$

$$G(\alpha,\varphi,I) = \frac{I}{\sqrt{3}}[1-\sqrt{2}\tan\phi\cos(\frac{\pi}{3}+\alpha)]$$

$$R(\alpha,\varphi,I) = \frac{I}{\sqrt{3}}[1+\sqrt{2}\tan\phi\cos(\frac{2\pi}{3}+\alpha)]$$

…you do not need to remember these formulae only why/how this is transformation useful?

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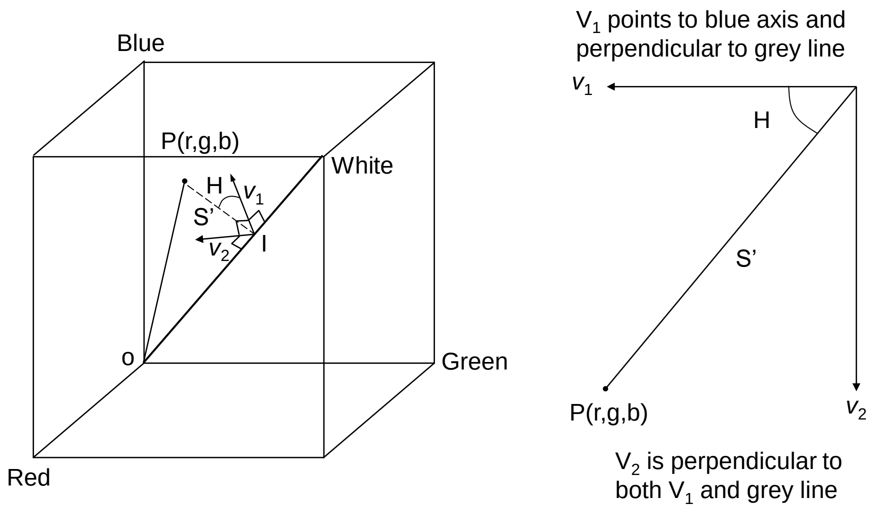
Matrix operation of RGB-HSI and HSI-RGB transformation

RGB-HSI transformation can also be derived via matrix operations and a coordinate rotation of the colour cube, aided by sub-coordinates of v_1 and v_2.



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RGB-HSI transformation

$$\begin{pmatrix} I \\ v_1 \\ v_2 \end{pmatrix} = \begin{pmatrix} 1/3 & 1/3 & 1/3 \\ -1/\sqrt{6} & -1/\sqrt{6} & 2/\sqrt{6} \\ 1/\sqrt{6} & -2/\sqrt{6} & 0 \end{pmatrix} \begin{pmatrix} R \\ G \\ B \end{pmatrix}$$

$$H = \arctan(v_2 / v_1) \qquad S' = \sqrt{v_1^2 + v_2^2} \qquad S = \arctan \frac{S'}{\sqrt{3} I}$$

HSI-RGB (inverse) transformation

$$\begin{pmatrix} R \\ G \\ B \end{pmatrix} = \begin{pmatrix} 1 & -1/2\sqrt{6} & 3/2\sqrt{6} \\ 1 & -1/2\sqrt{6} & -3/2\sqrt{6} \\ 1 & 1/\sqrt{6} & 0 \end{pmatrix} \begin{pmatrix} I \\ v_1 \\ v_2 \end{pmatrix} \qquad \begin{aligned} v_1 &= S' \cos 2\pi H \\ v_2 &= S' \sin 2\pi H \end{aligned}$$

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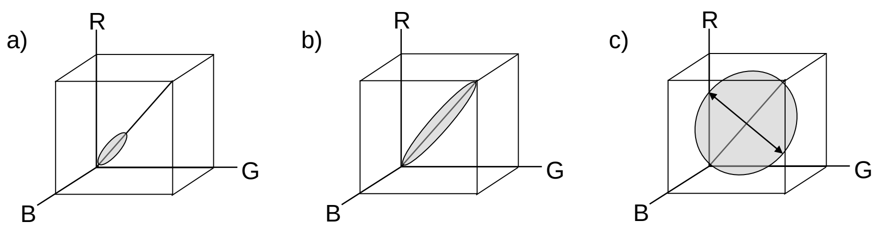
3.2 Spectral enhancement via **Decorrelation Stretch**

High correlation generally exists among spectral bands of all multi-spectral images.

a) So the original (raw) image band information (displayed in RGB) forms a slim cluster along the grey line and occupies only a very small part of the colour cube space (a)

b) Contrast enhancement on individual bands can elongate the cluster in the colour cube but cannot increase the volume of the cluster because such a stretch changes only the intensity and only makes the cluster longer (as in b).

c) To increase the volume of data cluster in the colour cube, it should be expanded in both directions (along and perpendicular to the grey line). This is equivalent to stretching both I and S components (as in c).



a) HSI based Decorrelation Stretch (HSIDS)

The HISDS technique involves three steps:

1. Transformation from RGB >> HSI
2. **Saturation component stretching**
3. Transformation from HSI >> RGB

- In the second step, H could be also stretched….
  - **But**, in the inverse transform (back to RGB display), the output colours may not be the same as those in the original image = spectral properties will have been changed!
  - This ambiguity can make image interpretation very difficult.
- The limited H range of a colour composite image is mainly caused by colour bias.
  - If the average brightness of one band is significantly higher than those of the other two bands, the colour composite will have an obvious colour ‘cast’ of the primary colour assigned to the band of highest brightness.
  - It is therefore better to use BCET to remove inter-band colour bias and thus to increase the H variation of a colour composite.
- The wider H value range achieved via BCET maximises the spectral information shown in H (rather than in S and I) this is fundamentally different from achieving a wide H range by stretching the H component itself.

- We can also use a **simple linear stretch** with automatic clipping or an interactive piecewise linear stretch can **effectively eliminate colour bias** (before HSI transformation).
- So, in summary, an **optimised HSIDS** transformation is achieved with an extra step:

1. **BCET stretch (or linear stretch with appropriate clipping).**
2. RGB-HSI transformation
3. Saturation component stretching (and intensity)
4. Inverse HSI-RGB transformation

- The effect of HSI transform based saturation stretch is similar to another kind of decorrelation stretch based on principal component analysis (as you will see next week).
- The difference between them is that HSIDS is interactive and flexible based on user observation of the saturation image and its histogram, whilst PCADS is based on image scene statistics alone…..

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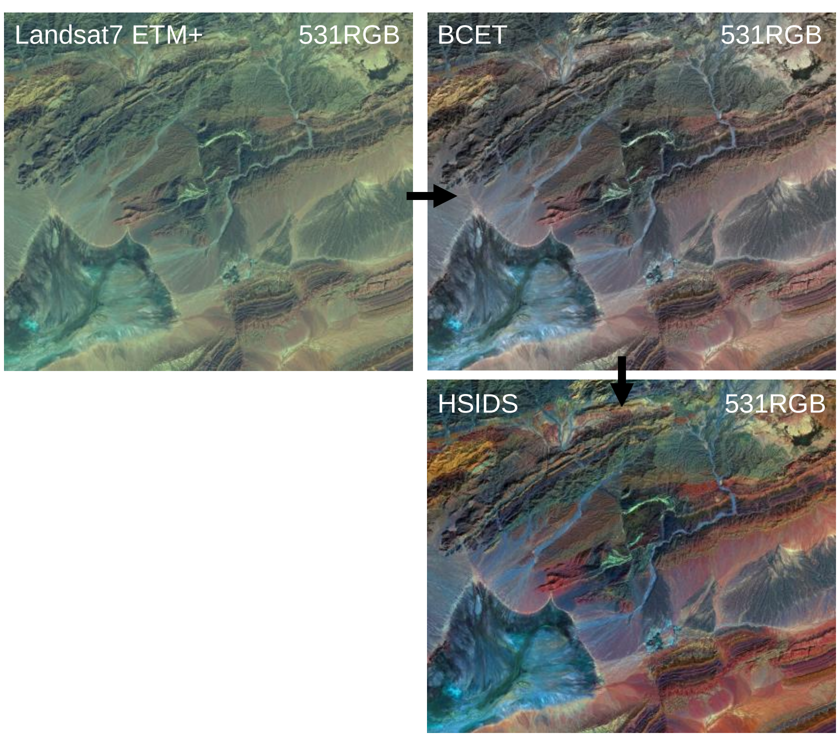

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- HSIDS **enhances the colour saturation** of a colour composite image and thus effectively improves the visual quality on image spectral information **without significant distortion of image spectral characteristics**.
- The resulting images are therefore easy to understand and interpret.
- Statistically, the processing **reduces the inter band correlation** as shown in the table below.

The correlation coefficients before and after decorrelation stretch of the Landsat-7 ETM+ Bands 5, 3 and 1 RGB colour composite shown in the previous slide.

Correlation Matrix **before** HSIDS					Correlation Matrix **after** HSIDS			
	Band 1	Band 3	Band 5			Band 1	Band 3	Band 5
Band 1	1.00	0.945	0.760		Band 1	1.00	**0.842**	**0.390**
Band 3	0.945	1.00	0.881		Band 3	0.842	1.00	**0.695**
Band 5	0.760	0.881	1.00		Band 5	0.390	0.695	1.00

Bands 1, 2 & 3 are less well correlated after

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b) Direct Decorrelation Stretch technique (DDS)

- Performs a saturation stretch without using RGB-HSI and HSI-RGB transformations.
- DDS achieves the same effect as the HSIDS but involves **only simple arithmetic operations** and can be **controlled quantitatively**.
- DDS is much faster, more flexible and more effective than HSIDS

  ……………..Sounds good but how does it work?
- A colour vector P and the grey line define a plane or a slice of the RGB cube. If we remove this slice (as shown in next figure), the grey line, full saturation line and maximum intensity line form a triangle that includes all the colours with the same hue but various intensities and saturations.
- P is between the grey (achromatic) line and the maximum saturation (chromatic) line and it can be considered as a sum of two vectors: vector ***a*** representing the **achromatic (zero saturation)** component or the white light in the colour, and vector ***c*** representing **chromatic (full saturation)** component that is relevant to the pure colour of the hue.

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Given $\mathbf{P} = (r, g, b)$ Let $a = Min(r, g, b)$

Then $\mathbf{a} = (a, a, a)$

$\mathbf{c} = (r - a, g - a, b - a)$

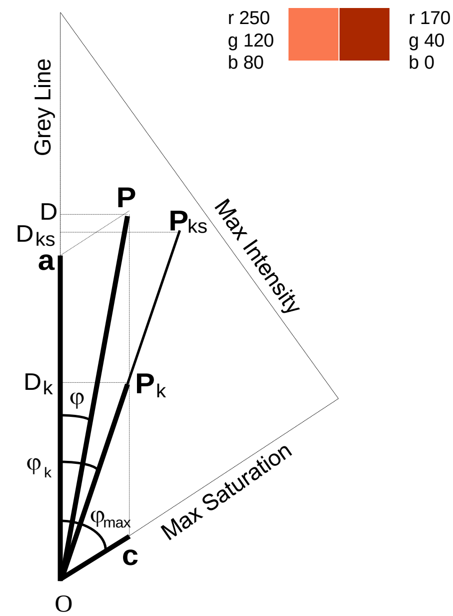
$= \mathbf{P} - \mathbf{a}$

Or $\mathbf{P} = \mathbf{a} + \mathbf{c}$

A direct decorrelation stretch is achieved by reducing the achromatic component (a) of the colour vector P, as defined below:

$$\mathbf{P}_k = \mathbf{P} - k\mathbf{a}$$

where k is an achromatic factor and $0<k<1$.



Liu & Moore, 1996. DDS technique for RGB colour composition, IJRS, 17, 5, p1005

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DDS cont'd

- So this operation shifts the colour vector $\mathbf{P}$ away from the achromatic line to form a new colour vector $\mathbf{P}_k$ with increased saturation ($\varphi_k > \varphi$) but with decreased intensity ($OD_k < OD$).
- To restore the intensity to a desired level, linear stretch can then be applied to each image in red, green and blue layers. This will elongate P_k to P_{ks} , with the same hue and saturation as P_k but with increased intensity ($OD_{ks} > OD_k$).
- DDS operation does not affect hue since it only reduces the achromatism of the colour and leaves the hue (represented by c) unchanged. This is easy to understand if we re-write the DDS formula as:

$$\mathbf{P}_k = \mathbf{P} - k\mathbf{a} = \mathbf{c} + \mathbf{a} - k\mathbf{a} = \mathbf{c} + (1-k)\mathbf{a}$$

- The numerical operations for the DDS are:

$$r_k = r - ka = r - k\min(r, g, b)$$
$$g_k = g - ka = g - k\min(r, g, b)$$
$$b_k = b - ka = b - k\min(r, g, b)$$

The final colour saturation of the output image is controlled (scaled) by the achromatic factor ***k***.

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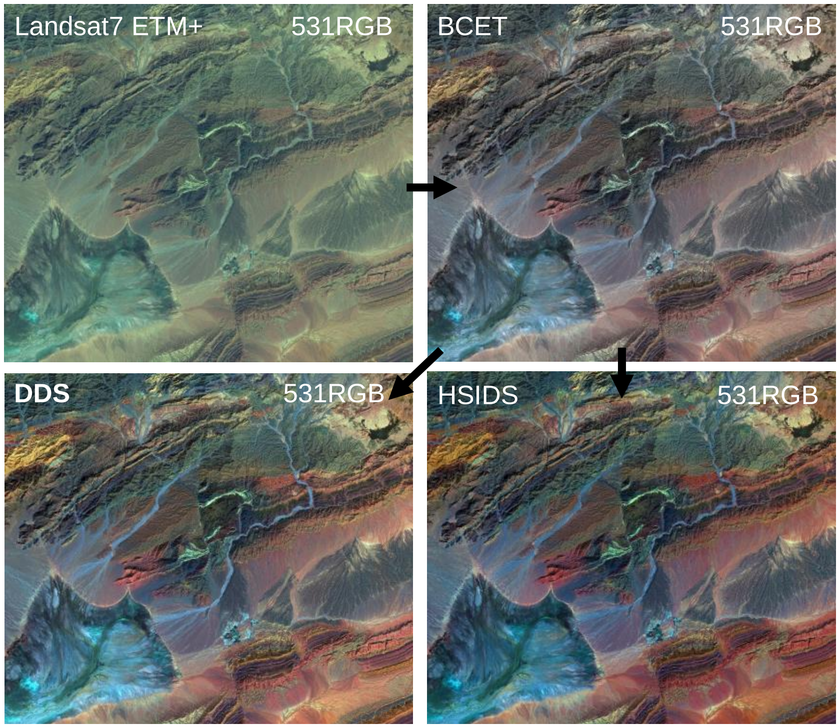

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DDS cont'd

- The final colour saturation of the output image is controlled (scaled) by the achromatic factor *k*.
- As already stated in the HSIDS, the 3 bands for colour composition must be well stretched (e.g. BCET or linear stretch with appropriate clipping) before the DDS is applied.
- In DDS, the scaling value *k* can be specified by the user. It should be based on the saturation level of the original colour composite. The lower the saturation of an image is, the greater the *k* value should be (within the range of *0 - 1*)
- *k = 0.5* is generally good for most cases.
- Let's compare an initial BCET colour composite with the DDS colour composites using *k* = 0.3, *k* = 0.5 and *k* = 0.7.

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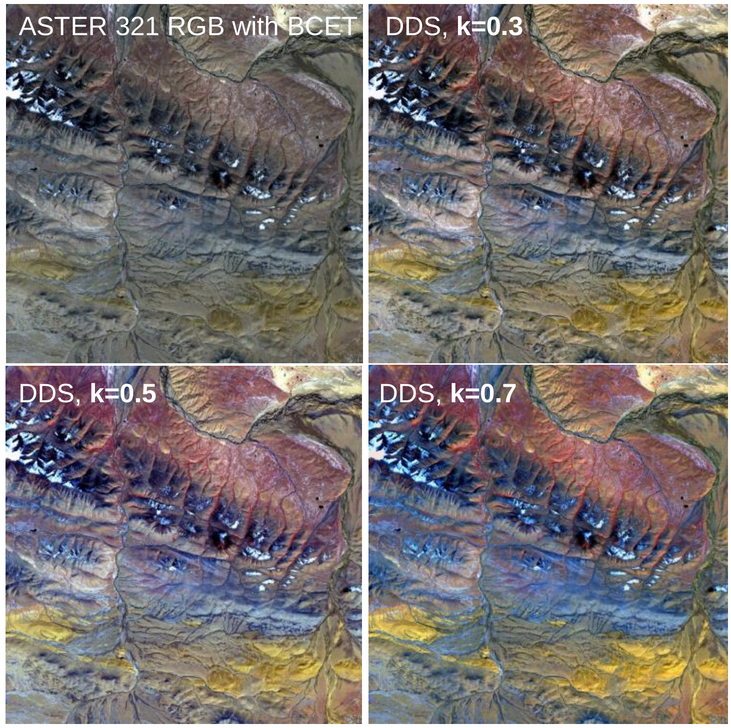
Effect of varying k



All DDS images show increased saturation without distortion of hue, in comparison with the BCET colour composite

Their saturation and intensity increases with the size of *k*.

The merits of simplicity and quantitative control of DDS are obvious

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3.3 **Data fusion techniques**

e.g. For resolution fusion or ‘Pan-sharpening’ (& for fusing multi-source data)

Can be achieved by fusing a low- and a high-resolution image of the same area (*e.g.* a Landsat 30 m with a SPOT panchromatic 10 m)

Low resolution CC (30m)   High resolution Pan (15m)   Pan-sharpened CC (15m)

The resultant fused (pan-sharpened) image is a mixture of **low-resolution spectral information** (from the low-resolution colour composite (cc)) and **high-resolution spatial and textural detail** (from the Panchromatic image).

There are several commonly used methods – some are better than others..

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a) RGB-HSI transformation for pan-sharpening

Resolution fusion (or 'Pan-sharpening') achieved via the following steps:

1. Geo- or co-reference a low- and a high-resolution image of the same area (*e.g.* a Landsat 30 m with a SPOT panchromatic 10 m)
2. RGB-HSI transformation on the low-res colour composite image
3. **Replace low-res Intensity component with high-res image**
4. HSI-RGB transformation for display

- The fused or pan-sharpened image is a mixture of low-resolution spectral information and high-resolution spatial and textural detail
- Overall resolution is apparently improved but colour distortion is unavoidably introduced.
- The **colour distortion may be significant if the spectral range of the three MS colour composite bands is very different** from that of the Panchromatic band, i.e. the intensity component (as the summation of the three MS bands) is different from the Pan that is used for intensity replacement. NB look carefully at band widths first

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b) RGB-HSI multi-source data integration

e.g. fusing low-res geophysical data with high-res DEM, Pan image or other high-res data, achieved by the following steps:

1. Geo- or co-reference the low- & high- resolution datasets to be fused
2. RGB-HSI transformation on the low-res colour composite image
3. **Replace intensity component by geophysical or geochemical dataset**
4. HSI-RGB transformation for display

- The resultant image contains both spectral information of the original image bands and geophysical or geochemical information as intensity variation.
- The interpretation of such images needs experience on the datasets used - and may or may not be practically useful!
- A more productive method is to use the 'colour drape' technique in which a geophysical or geochemistry dataset is used as if it were a DEM (digital elevation model) with a colour composite image draped onto it in 3D perspective view.

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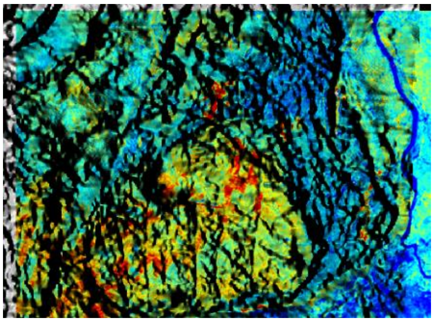
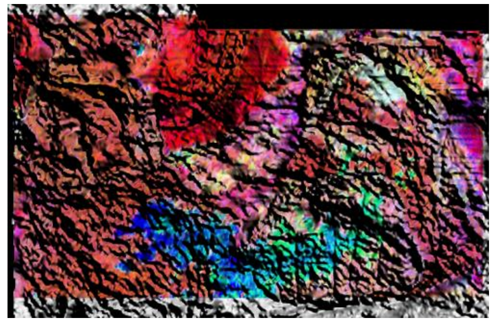
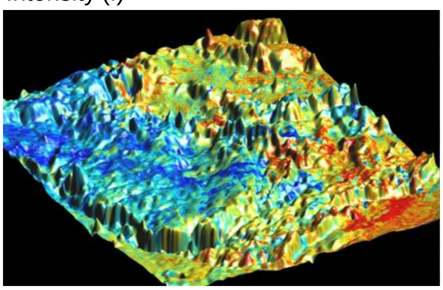


Landsat hydrated mineral ratio providing H and S, and magnetic susceptibility as Intensity (I)



Radiometric data (U, Th & Pb as RGB colour composite) providing H and S, and magnetic susceptibility as Intensity (I)



In 3D also, the intensity can be used as 'height' to provide a DEM surface. So H and S from a Landsat iron-oxide ratio here are draped on a surface representing magnetic susceptibility (I)

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c) *Brovey* transform data fusion (intensity modulation)

$$R_b = \frac{3RP}{R+G+B}$$

$$G_b = \frac{3GP}{R+G+B}$$

$$B_b = \frac{3BP}{R+G+B}$$

We can re-write the formulae on the left in a simpler format as follows:

$$R_b = R \times P / I$$
$$G_b = G \times P / I$$
$$B_b = B \times P / I$$

If image *P* is a higher resolution image, then above formulae performs image fusion and improves spatial resolution, or if *P* is a raster dataset of different source, multi-source data integration is performed.

The Brovey transform achieves a similar result to the HSI fusion technique but without carrying out the RGB-HSI and HSI-RGB transformations and thus **simpler and faster.** However, it introduces **colour distortion** as well.

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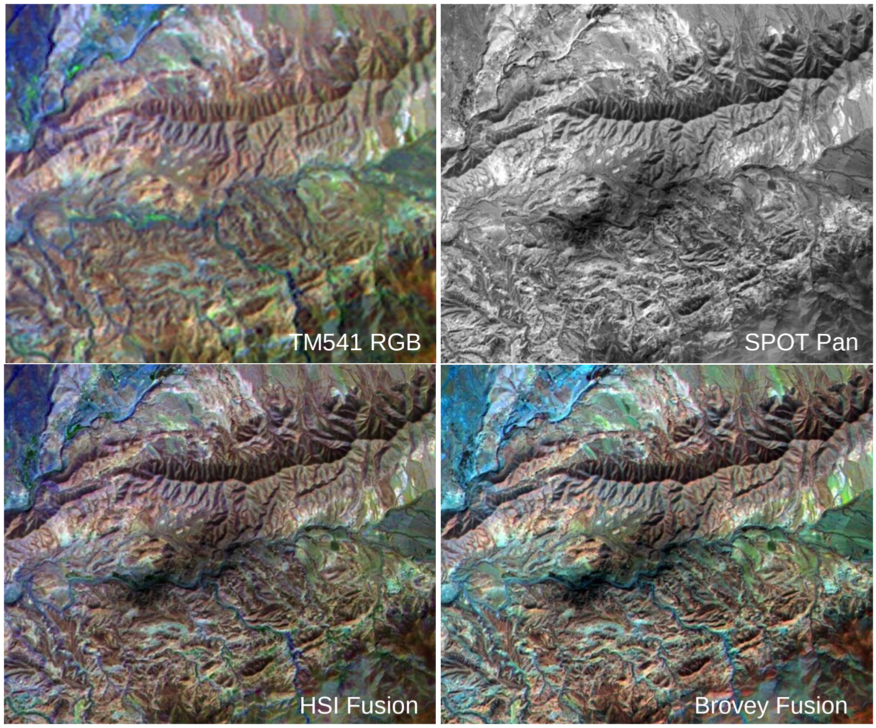

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A word of warning about HSI and Brovey methods

- Both HSI and Brovey transform image fusion techniques can cause colour distortion **if the spectral range of the intensity replacement (or modulation) image is different from the spectral range covered by the three bands used in a colour composite.**
  a) Inevitable in colour composites that do not use consecutive spectral bands.
  b) Can be severe in vegetated areas if the images are acquired in different growth seasons.
- **Preserving the original spectral properties is very important** for applications based on spectral signatures, such as lithology, soil and vegetation.
- The spectral distortion introduced by these fusion techniques is uncontrolled and unquantified because the images for fusion are often taken by different sensor systems, on different dates, or in different seasons.
  - Such fusion cannot really be regarded as spectral '*enhancement'* and should be avoided to prevent unreliable interpretation.

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d) Spectral-conservation data fusion technique - *Smoothing Filter based Intensity Modulation (SFIM)*

The **spectral distortion problem is only avoided if colour composites that use consecutive spectral bands which occupy the same spectral range as the panchromatic band used for the fusion**

- Limits their use to pan-sharpening and one band combination, e.g. True Colour or Standard False Colour composites (depending on the spectral range of the Panchromatic band)

However, the **Smoothing Filter based Intensity Modulation** (SFIM) technique (Liu, 1999) is a genuine spectral-conservation image fusion technique which is applicable to co-registered multi-resolution images.

How does it work?

Liu 2000. SFIM: a spectral preserve image fusion technique for improving spatial details, IJRS, 21, 18

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The DN value of a daytime optical image of reflective spectral band λ is mainly decided by two factors: the solar radiation impinging on the land surface or irradiance *E*(λ), and the spectral reflectance of the land surface ρ (λ)… $DN(\lambda) = \rho(\lambda)E(\lambda)$

Low resolution image: $DN(\lambda)_{low} = \rho(\lambda)_{low}E(\lambda)_{low}$

High resolution image: $DN(\gamma)_{high} = \rho(\gamma)_{high}E(\gamma)_{high}$

SFIM formula: $$DN(\lambda)_{SFIM} = \frac{DN(\lambda)_{low} \times DN(\gamma)_{high}}{DN(\gamma)_{mean}}$$

$$= \frac{\rho(\lambda)_{low}E\cancel{(\lambda)_{low}} \times \rho\cancel{(\gamma)_{high}}E(\gamma)_{high}}{\rho\cancel{(\gamma)_{low}}E\cancel{(\gamma)_{low}}}$$

$$\approx \rho(\lambda)_{low}E(\lambda)_{high}$$

where $DN(\lambda)_{SFIM}$ is the fused higher resolution pixel corresponding to $DN(\lambda)_{low}$ and $DN(\gamma)_{mean}$, which is the local mean of $DN(\gamma)_{high}$ over a neighbourhood equivalent to the resolution of $DN(\lambda)_{low}$

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General form of the SFIM algorithm is:

$$IMAGE_{SFIM} = \frac{IMAGE_{low} \times IMAGE_{high}}{IMAGE_{mean}}$$

- The ratio between $IMAGE_{high}$ and $IMAGE_{mean}$ in the formula cancels the spectral and topographical contrast of the high resolution image but **retains the high resolution textures**.
- The **SFIM image** of $DN(\lambda)_{SFIM}$ is a product of the **higher resolution spatial texture** introduced from the higher resolution image, $E(\gamma)_{high}$, **and the lower resolution spectral reflectance** of the original lower resolution image, $\rho(\lambda)_{low}$. It is therefore **independent of the spectral properties of the high resolution image** used for intensity modulation.
- SFIM can thus be understood as *a low resolution image directly modulated by high resolution textures* and the result is independent of the contrast and spectral variation of the higher resolution image.

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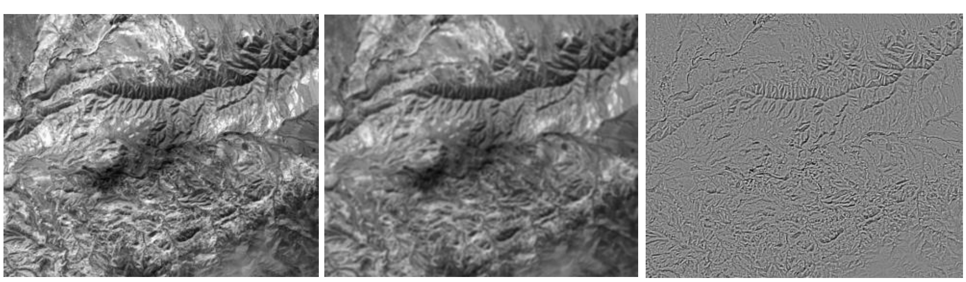

(a) (b) (c)

(a) Original SPOT Pan image (*$Image_{High}$*)

(b) Smoothed SPOT Pan image with a 5×5 smoothing filter (*$Image_{Mean}$*)

(c) The ratio image between (a) and (b) (= high-res textural information)

- SFIM can thus be understood as *a **low resolution image directly modulated by high resolution textures*** and the result is independent of the contrast, shadows and spectral variation of the higher resolution image.
- SFIM therefore honours the spectral properties as well as contrast of the original low resolution image

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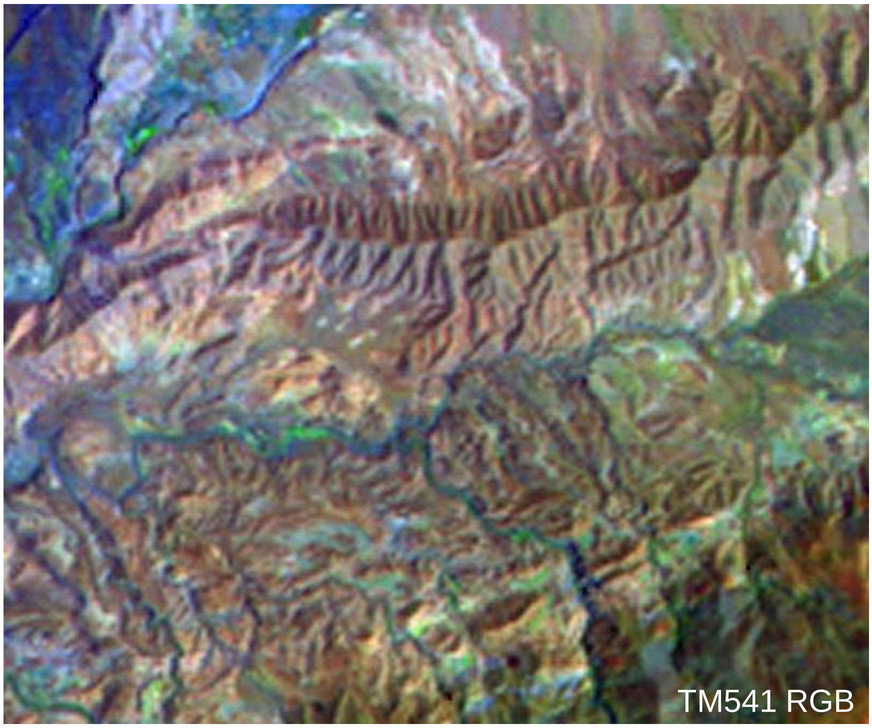

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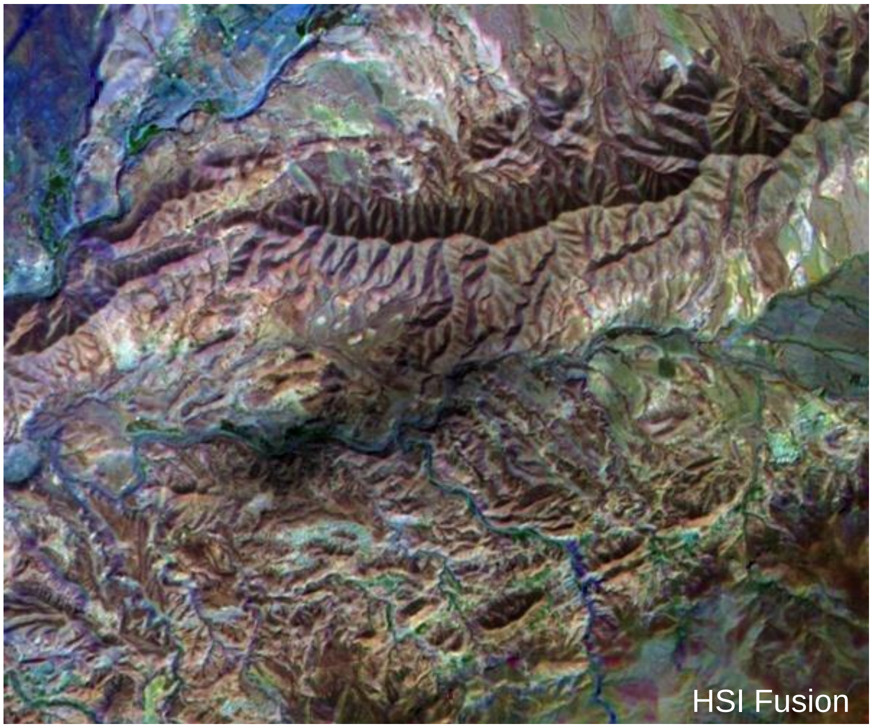

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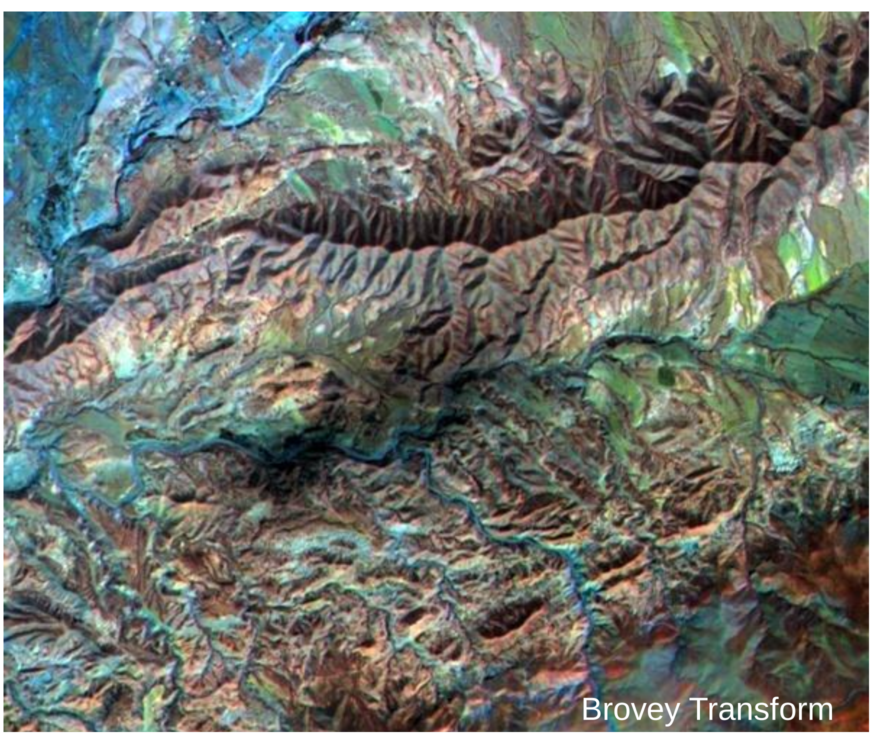

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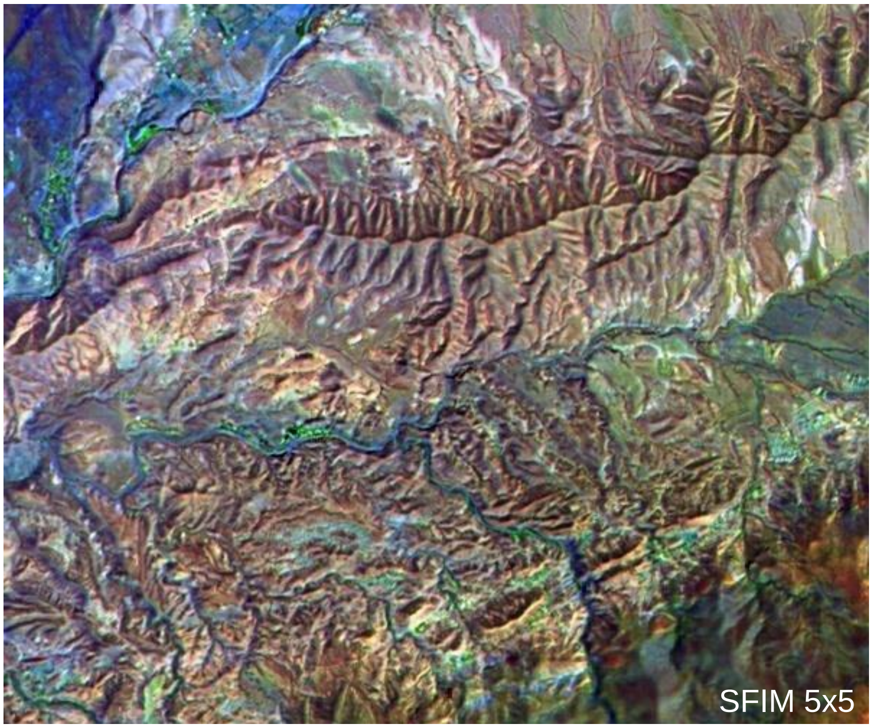

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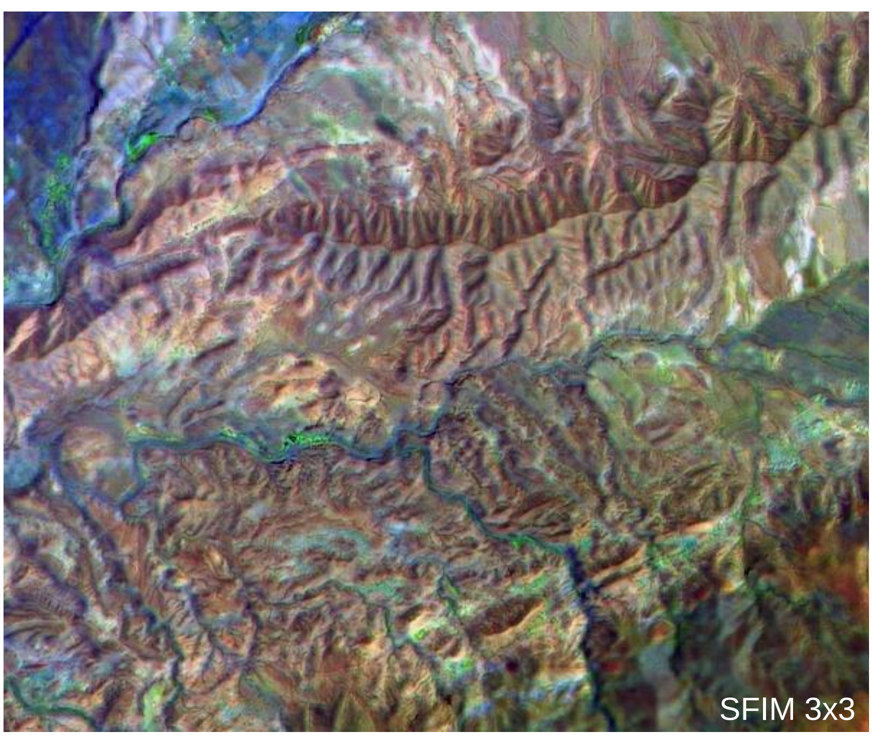

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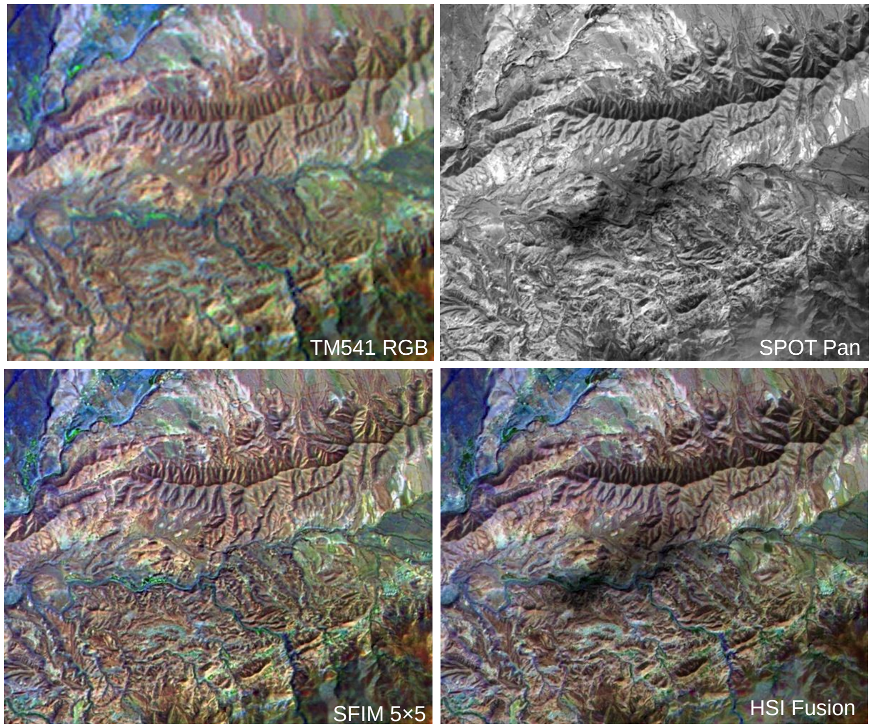
TM541 RGB
SPOT Pan
SFIM 5×5
HSI Fusion

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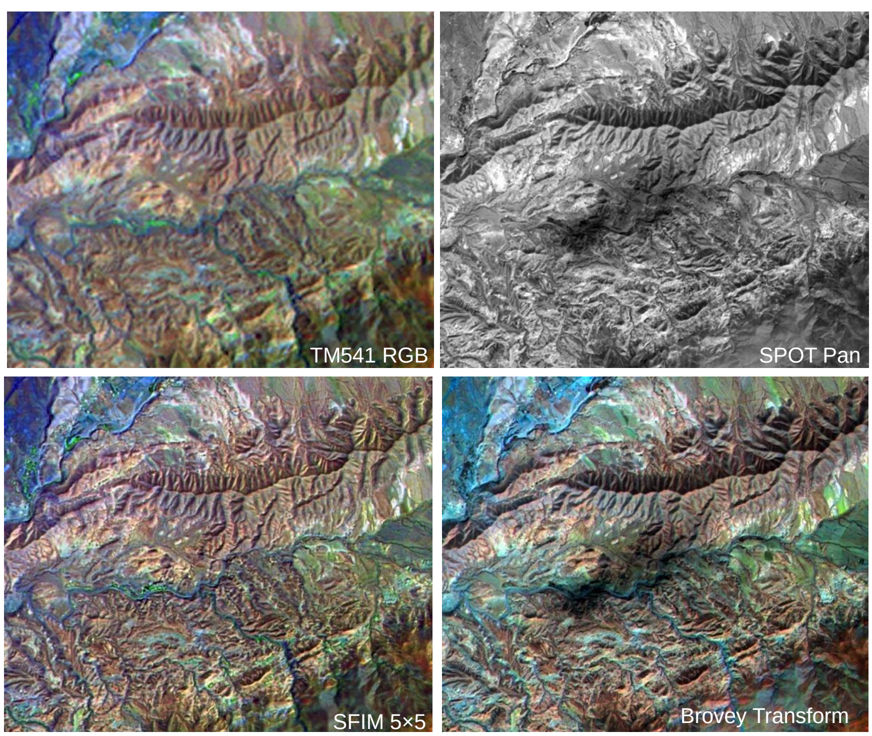
TM541 RGB
SPOT Pan
SFIM 5×5
Brovey Transform

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Landsat 8 OLI 432 RGB 30m Resolution

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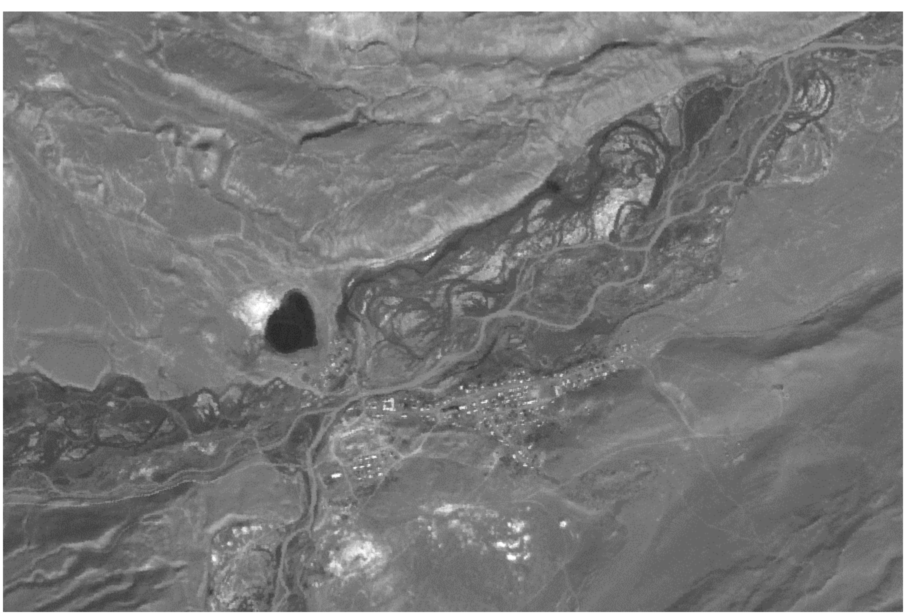
SPOT 5 Pan 5m Resolution



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Landsat 8 OLI 432 RGB – SPOT 5 Pan Fusion Image

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Summary of the SFIM

- For SFIM operations, the lower resolution image **<u>must be interpolated to the same pixel size</u>** as the higher resolution image by bilinear or cubic interpolation in the co-registration process.
- The advantage of the SFIM over the HSI and Brovey transform fusion technique is that it improves spatial details with the added benefit of **preserving image spectral properties** and contrast.
- However, The SFIM is **more sensitive to image co-registration accuracy** than the HSI and Brovey transform.
  - Inaccurate co-registration may cause blurring to edges in the fused images.
  - This problem can be alleviated using a smoothing filter with a kernel larger than the resolution ratio between the higher and lower resolution images. For instance, for TM (30m) and SPOT Pan (5m) fusion 5×5 and 7×7 filters will produce better results than a 3×3 filter.
  - In ESE we have developed an advanced pixel-wise image co-registration algorithm that resolve that problem.

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3.3 Colour coordinate transformation summary

- Colour quality can be described in Hue, Saturation and Intensity,
- The RGB-HSI transformation and the inverse transformation HSI-RGB can be derived based on either 3D geometry (or matrix operations) for coordinates rotation of the RGB colour cube.
- The RGB-HSI and HSI-RGB transformations allow manipulation of colour intensity, hue and saturation components separately with great flexibility.
- One major application is the saturation stretch based HSIDS technique that **enhance image colour saturation without altering the hues of the colours**.
- DDS is a clever short-cut based on colour vector decomposition in achromatic and chromatic components, the **DDS performs saturation stretch directly** in RGB domain without involving the RGB-HSI and HSI-RGB transformations.
- Another application of RGB-HSI and HSI-RGB transformations is **data fusion to improve image spatial resolution** and **integrate raster datasets** from different sources via intensity replacement.
- The Brovey transform is an intensity modulation based technique achieving similar data fusion results though the principle is different.
- The SFIM is a truly **spectral preservation pan-sharpening** technique which requires precise image co-registration.

3.4 Revision Questions

1. Using a diagram of RGB colour cube to explain the mathematic definition and physical meaning of intensity, hue and saturation.
2. What are the value ranges of intensity, hue and saturation according to the RGB colour cube model of RGB-HSI transformation?
3. Why RGB-HSI is a useful image processing technique?
4. Describe the principle of decorrelation stretch (DS) with the aid of diagrams.
5. Describe the major steps of HSI DS and explain how the image inter-band correlation is reduced and why.
6. What is the drawback of stretching the hue component in the HSI decorrelation stretch? How can we expand the value range of the hue component without stretching the hue component directly?
7. Using a diagram to explain the principle of DDS. In what senses are DDS and HSI DS are similar, and different?
8. How to improve the spatial resolution of a 30m resolution TM colour composite with a 10m resolution SPOT panchromatic image using RGB-HSI transformation and Brovey transform?
9. Explain the major problem of image fusion using RGB-HSI transformation and Brovey transform.
10. How does SFIM achieve pan-sharpening which preserves spectral properties?