Earth Observation:
Data, Processing and Applications

Volume 1X: Data—Appendices

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Publisher:
Australia and New Zealand CRC for Spatial Information

ISBN [ONLINE]:
978-0-9943019-6-3

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Recommended Citation for Volume 1X:
CRCSI (2018) *Earth Observation: Data, Processing and Applications. Volume 1X: Data—Appendices*. (Eds: Harrison, B.A., Jupp, D.L.B., Lewis, M.M., Forster, B.C., Mueller, N., Smith, C., Phinn, S., Hudson, D., Grant, I., Coppa, I.) CRCSI, Melbourne.

Latest Revision:
October 2025

Background image on previous page: This HyMap airborne hyperspectral image mosaic over the Dalhousie Springs Complex, in far-northern South Australia. It is displayed using the 0. 0.636 μm band as red, the 0.544 μm band as green and the 0.467 μm band as blue. This region features extensive wetlands in an arid environment, fed by Great Artesian Basin spring flows. This imagery was acquired by HyVista Corporation for the *Allocating Water and Maintaining Springs of the Western Great Artesian Basin* project in 2009. **Source:** Megan Lewis, University of Adelaide

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Appendix 1 Recommended Reading

A1.1 Professional Journals

- Asian Journal of Remote Sensing
- Canadian Journal of Remote Sensing
- Geocarto International
- IEEE Transactions on Geoscience and Remote Sensing
- International Journal of Digital Earth
- International Journal of Geographical Information Systems
- International Journal of Remote Sensing
- Journal of Applied Meteorology
- Journal of Geophysical Research
- Journal of Ocean Engineering
- Marine Geodesy
- Photogrammetria
- Photogrammetric Engineering and Remote Sensing
- Remote Sensing
- Remote Sensing in Ecology and Conservation
- Remote Sensing of Environment
- Sensors
- Space Technology: Industrial and Commercial Applications

A1.2 Textbooks

ASPRS: *Manual of Remote Sensing*. 3rd edn (Ed: Rencz, A.N.) John Wiley and Sons.
Volume 1—*Earth Observing Platforms and Sensors* (Eds: Morain, S.A., Budge, A.M.)
Volume 2—*Principles of Imaging Radar* (Eds: Henderson, F.M., and Lewis, A.J.)
Volume 3—Remote Sensing for the Earth Sciences (Ed: Rencz, A.)
Volume 4—Remote Sensing for Natural Resource Management and Environmental Monitoring (Ed: Ustin, S.L.)
Volume 5—*Remote Sensing of Human Settlement* (Eds: Ridd, M.R., and Hipple, J.D.)

Campbell, J.B., and Wynne, R.H. (2011) *Introduction to Remote Sensing*. 5th edn. Guilford Press, New York.

Castleman, K.R. (1996) *Digital Image Processing*. Prentice Hall.

Chuvieco, E., and Huete, A. (2010) *Fundamentals of Satellite Remote Sensing*. CRC Press, Boca Raton.

Cracknell, A. (2007) *Introduction to Remote Sensing*. 2nd edn. Taylor and Francis.

Curran, P.J. (1985) *Principles of Remote Sensing*. Longman.

Drury, S.A. (2001) *Image Interpretation in Geology* 3rd edn. Blackwell Science.

Elachi, C., and van Zyl, J. (2006) *Introduction to the Physics and Techniques of Remote Sensing*. 2nd edn. John Wiley and Sons.

Gibson, P.J. and Power, C. H. (2000) *Introductory Remote Sensing Principles and Concepts*. London, Routledge.

Gonzalez, R.C., and Woods, R.E. (2018) *Digital Image Processing*. Pearson Educational Inc., New York.

Jensen, J.R. (1986) *Introductory Digital Image Processing*. 2nd edn. Prentice Hall.

Jensen, J.R. (2007) *Remote Sensing of the Environment*: An Earth Resource Perspective. 2nd edn. Prentice Hall.

Lillesand, T.M. and Kiefer, R.W. (2000) *Remote Sensing and Image Interpretation*. 4th edn. John Wiley and Sons, New York.

Richards, J. (2009) *Remote sensing with imaging radar*. Springer, Heidelberg.

Richards, J.A. and Xiuping, J. (2006) *Remote Sensing Digital Image Analysis: An Introduction*. 4th edn. Springer.

Background image: Landsat-5 image, acquired on 29 April 2011 over Shark Bay, WA, displayed as true colour (using bands 3, 2, 1 as RGB).
Source: Norman Mueller, Geoscience Australia

Appendix 2
Professional Societies

International Society for Photogrammetry and Remote Sensing (ISPRS): *http://www.isprs.org/*

National societies that are members of the ISPRS are listed here: *http://www.isprs.org/links/members.aspx*
They include:
American Society for Photogrammetry and Remote Sensing (ASPRS): *http://www.asprs.org/*
The Remote Sensing and Photogrammetry Society (RSPSoc): *http://www.rspsoc.org.uk/*
IEEE Geoscience and Remote Sensing Society (GRSS): *http://www.grss-ieee.org/*
Canadian Aeronautics and Space Institude (CASI): *http://www.casi.ca*

Earth Observation Australia (fEOA): http://www.eoa.org.au

The Colour Society of Australia is concerned with various aspects of colour measurement and perception and thus has relevance to remote sensing and image processing: *http://www.coloursociety.org.au*

Background image: Sentinel-2 image of Port Alma, Queensland, acquired on 24 January 2016, showing saltpans and mangroves in Fitzroy River delta (displayed using bands 11, 8, 3 as RGB). **Source:** Norman Mueller, Geoscience Australia

Appendix 3
EO Data and Information Sources

A3.1 Australian

Government

Geoscience Australia (GA): *http://www.ga.gov.au/scientific-topics/earth-observation*

Introduces remote sensing concepts and provides information on data sources. Includes a catalogue of satellite images that may be downloaded or purchased, plus facts and examples for different types of images.

Regional Copernicus Data Hub: *http://www.copernicus.gov.au/*

Serves Sentinel satellite data.

Commonwealth Scientific and Industrial Research Organisation (CSIRO):

Australian-waters Earth Observation Phytoplankton-type Products Data Base: *http://aesop.csiro.au/*

Serves marine in-situ optical data.

Landgate: *https://www.landgate.wa.gov.au/maps-and-imagery*

Bureau of Meteorology: *http://bom.gov.au*

Marine Water Quality Dashboard: *http://www.bom.gov.au/marinewaterquality/*

Serves satellite derived water quality information and data.

Reef Temp: *http://www.bom.gov.au/environment/activities/reeftemp/reeftemp.shtml*

Serves satellite information on coral bleaching risk.

Academia

Terrestrial Ecosystem Research Network (TERN): *http://www.tern.org.au*

TERN Auscover Remote Sensing Data Facility: *http://www.auscover.org.au*

TERN SuperSites: *http://www.supersites.net.au*

TERN OzFlux: *http://www.ozflux.org.au*

Integrated Marine Observing System (IMOS): *http://www.imos.org.au*

Australian Ocean Data Network (AODN): *https://portal.aodn.org.au/*

Serves marine in-situ and satellite observations made under IMOS.

IMOS Ocean Current: *http://oceancurrent.imos.org.au/*

Serves satellite observations of currents and sea surface temperature.

University of Queensland—Remote Sensing Toolkit: *https://sees-rsrc.science.uq.edu.au/rstoolkit/*

KEJOYCE.COM: *http://www.kejoyce.com/education.html*

Flinders University:

Airborne Research Australia (ARA): *http://www.airborneresearch.org.au*

Background image: Landsat-5 image of Australia's most devastating bushfires, known as the Black Saturday Fires, in Victoria, which ignited on 7 February 2009. This image was acquired on 17 February and shows the extensive areas impacted by the fires as brown scars in the centre of the image. These fires have been rated as the world's worst fire event, involving 173 deaths, destruction of over 2,000 houses, and burning of over 400,000 ha. This image is displayed using bands 5, 4, 2 as RGB. **Source:** Norman Mueller, Geoscience Australia

Private Companies

AirAffairs: *http://www.airaffairs.com.au*

An Australian company providing specialised airborne and engineering services, including bushfire mapping.l

Airbus Defence and Space: *https://airbusdefenceandspace.com*

An international company developing both military aircraft and space systems, including a comprehensive range of EO satellites systems, as well as communications, intelligence and security systems.

Digital Globe: *https://www.digitalglobe.com*

An international company operating constellations of high spatial resolution satellites.

Geoimage: *http://www.geoimage.com.au/media/brochures*

An Australian company distributing imagery. Informative web site and brochures on remote sensing principles, applications and image types.

Nearmap: *http://au.nearmap.com*

An Australian company with a proprietary technology platform that combines aerial camera systems, rapid image processing and data visualisation applications, enabling it to regularly capture and publish high resolution aerial surveys.

Spookfish: *https://www.spookfish.com*

An Australian company using a dynamic motion camera to capture high resolution imagery across the continent to deliver two- and three-dimensional datasets.

Fugro Spatial Solutions: *http://www.fugrospatial.com.au*

Australia's largest aerial survey company.

Hyvista Corporation: *http://www.hyvista.com*

An Australian company specialising in the supply of airborne hyperspectral remote sensing data, large format digital imagery and value-added information products.

AAM Group: *http://www.aamgroup.com*

An Australian company specialsing in the collection, analysis, presentation and delivery of geospatial information.

A3.2 International

Committee on Earth Observation Satellites (CEOS): *http://www.ceos.org*

International committee coordinating civil spaceborne observations of the Earth.

EO Handbook: *http://www.eohandbook.com*

A3.3 USA

Government

National Aeronautical and Space Agency (NASA): *http://www.nasa.gov*

Landsat Science—Education: *http://landsat.gsfc.nasa.gov/education/*

A very comprehensive website covering remote sensing theory and history, image processing, applications and specialist forms of remote sensing.

NASA World Wind: *http://worldwind.arc.nasa.gov*

Viewing of images from several sensors for the world.

NASA Goddard Space Flight Centre: *http://imagine.gsfc.nasa.gov/docs/sats_n_data/sats_n_data.html*

Aster Spectral Library: *http://speclib.jpl.nasa.gov*

NASA Aeronet-Ocean Colour: *http://aeronet.gsfc.nasa.gov/cgi-bin/type_one_station_seaprism_new?site=Lucinda&nachal=2&level=1&place_code=10*

Serves a few of the Lucinda above-water measurements (IMOS; see Section 10).

United States Geological Survey (USGS): *http://www.usgs.gov*

USGS Global Visualization Viewer: *http://glovis.usgs.gov*

GloVis allows you to visually search, download and order various satellite data including Landsat.

USGS Spectroscopy: *http://speclab.cr.usgs.gov/PAPERS.refl-mrs/refl4.html#section1.1*

Chapter 1 from Volume 3 in Manual of Remote Sensing, includes detailed background information relating to spectroscopy of rocks and minerals.

USGS Spectral Library: *http://speclab.cr.usgs.gov/index.html*

National Oceanic and Atmospheric Administration (NOAA): *http://www.noaa.gov*

Academia

The Pennsylvania State University: *https://www.e-education.psu.edu/geog883/*

University of Colorado at Boulder

The Geographer's Craft: *http://www.colorado.edu/geography/gcraft/contents.html*

National Earth Science Teachers Association

Windows to the Universe: *http://www.windows2universe.org*

Federation of American Scientists

Remote Sensing Tutorial (Nicholas Short): *http://www.fas.org/irp/imint/docs/rst/Front/overview.html*

Private Companies:

The Light Measurement handbook: *http://www.intl-lighttech.com/services/light-measurement-handbook*

TNT Mips

Introduction to Remote Sensing of the Environment: *http://www.microimages.com/documentation/Tutorials/introrse.pdf*

ERDAS/ERmapper: *http://www.erdas.com*

A3.4 Canada

Canada Centre for Remote Sensing, Natural Resources Canada: *http://www.nrcan.gc.ca/earth-sciences/geomatics/satellite-imagery-air-photos/satellite-imagery-products/educational-resources/9309*

A3.5 Europe

European Space Agency (ESA): *http://www.esa.int/ESA*

Science Education through Earth Observation for High Schools (SEOS, ESA/ESRIN): *http://www.seos-project.eu/modules/remotesensing/remotesensing-c00-p01.html*

eLearning tutorials

Advanced Training Course on Land Remote Sensing: *http://earth.esa.int/landtraining07/*

University College London: *http://www2.geog.ucl.ac.uk/~mdisney/teaching/PPRS/PPRS_5/principles5.pdf*

A3.6 Asia

Japanese Aerospace Exploration Agency (JAXA): *http://global.jaxa.jp*

Centre for Remote Imaging, Sensing and Processing

Principles of Remote Sensing (S.C. Liew): *http://www.crisp.nus.edu.sg/~research/tutorial/rsmain.htm*

Appendix 4 Photographic Products

The first remote sensors were aerial cameras recording images onto light-sensitive film (see Sardar (1997), for a summary of the historical development of remote sensing). A major advantage of photographic imagery is its technical simplicity in terms of processing and interpretation. An important disadvantage, however, is that the utility of photographic products are controlled by the quality of acquisition and processing, especially for monitoring applications where multiple photographs acquired on different dates or for different areas need to be compared.

A4.1 Photographic Film

The range of wavelengths that may be detected by traditional (film-based) photographic devices is limited by the sensitivities of the film and filter(s) being used in the camera. The spectral sensitivity of photographic film can range from ultraviolet to near infrared wavelengths. Filters may be used in conjunction with different film types to restrict the wavelengths being recorded or reduce the effect of atmospheric haze. Multi-band cameras, which simultaneously record multiple photographic impressions of an object, may be used to simulate a multi-spectral image. Such cameras use varying film and filter combinations to record different spectral regions in each photograph.

Photographic film may be sensitive to wavelengths over a single range (such as single layer black and white film) or in three wavelength ranges (such as three-layer colour film). The four types of film that may be used for aerial photography are:

- black and white visible, or 'panchromatic' (sensitive to wavelengths in the range 0.3–0.7 μm)
- black and white near infrared
- colour visible
- false colour near infrared

There are two types of panchromatic film:

- 'mapping' film which has roughly equal sensitivity to all visible wavelengths. This is the most commonly used film for aerial photography. It may be used in conjunction with a 'minus-blue' (blue absorbing) filter to reduce the effects of atmospheric scattering and haze in the blue end of the EM spectrum; and
- 'reconnaissance' film which is less sensitive in the blue wavelength region to reduce the effect of atmospheric scattering.

Panchromatic film is sensitive to visible wavelengths in the range 0.3–0.7 μm (see Figure A4.1). The spectral sensitivity of black and white infrared film extends to about 0.9 μm in the near infrared region (see Figure A4.1). It can be used with a dark red absorption filter to record near infrared radiation only, or with appropriate filters to record selected regions in both visible and near infrared wavelengths.

As colour film is designed to mimic human vision, its three emulsion layers are sensitive to the three wavelength regions of blue, green and red.

The spectral sensitivity of colour infrared film differs from normal colour film. Colour infrared film is used in conjunction with a yellow (blue absorbing) filter to record green, red and infrared radiation onto its three emulsion layers. This relationship produces false colour imagery with characteristic colours for different land covers:

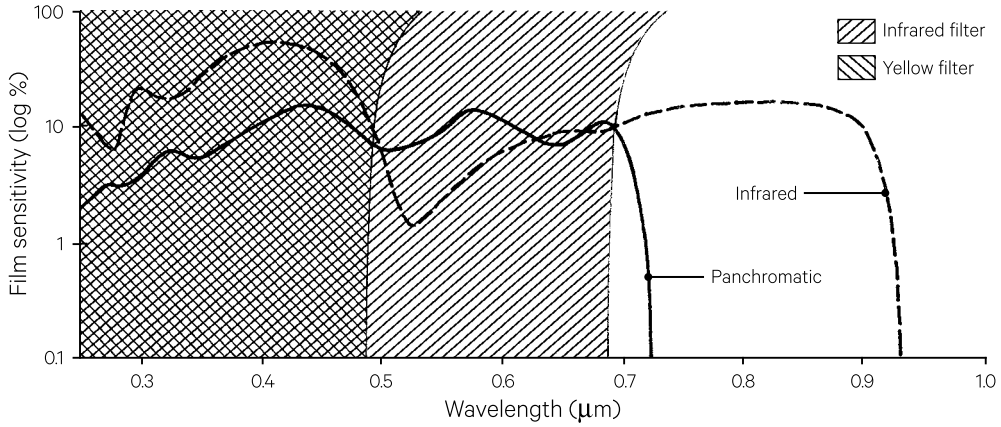
- green vegetation appears red;
- deep clear water is dark blue;
- turbid water is bright blue;
- red soil appears green; and
- bright urban areas appear pale blue.

The concepts of colour and colour mixing are introduced in Volume 1A and further discussed in Volume 2. The sensitivities of colour and colour infrared films are illustrated in Figure A4.2.

Background image: High resolution airborne image acquired by Nearmap on 5 May 2016, showing Opera House and Circular Quay in Sydney. **Source:** © Nearmap

Figure A4.1 Spectral sensitivities of panchromatic film

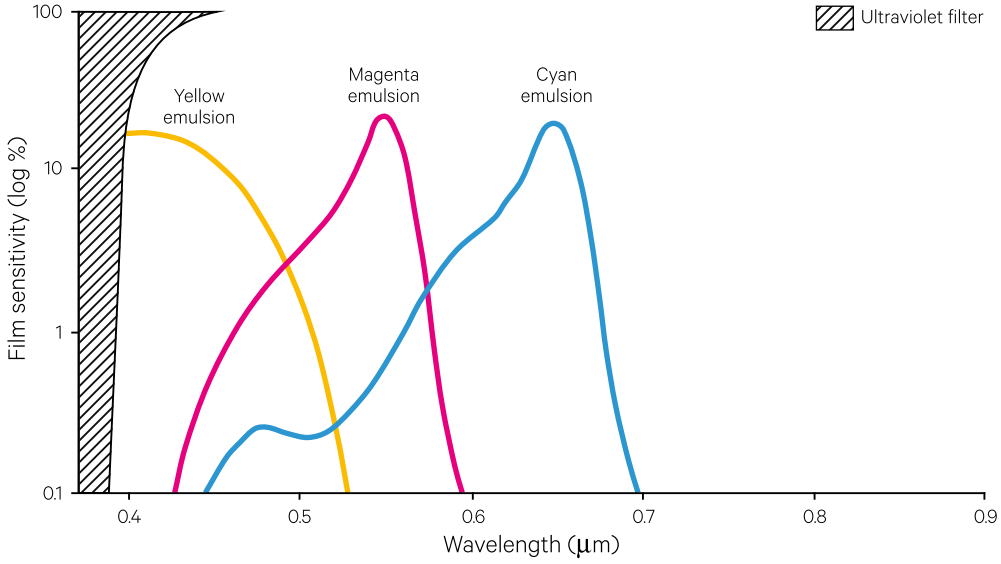
This graph compares the spectral sensitivity of panchromatic 'visible' film and 'infrared' film. It also shows the spectral impact of using a yellow filter.



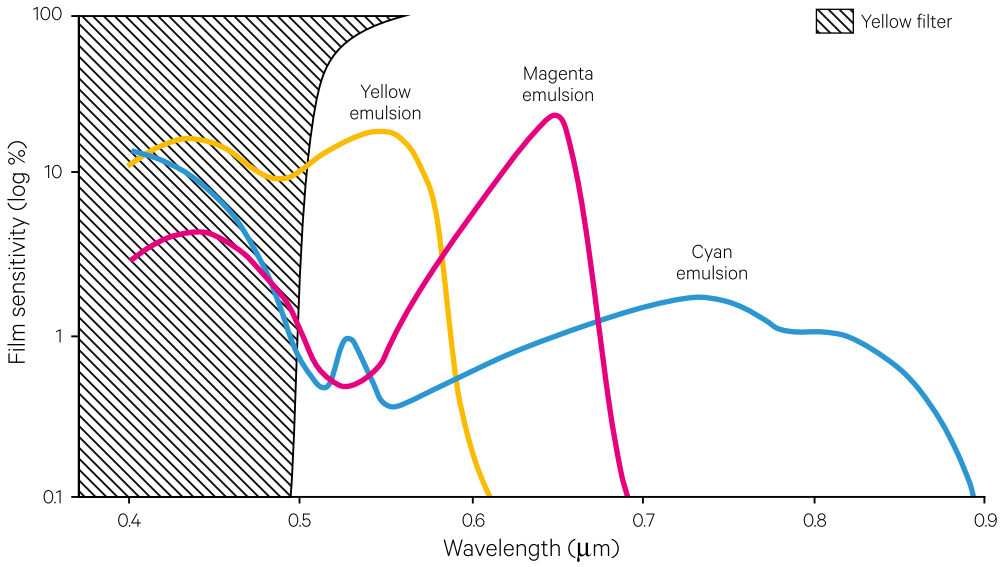
Source: Harrison and Jupp (1989) Figure 13

Figure A4.2 Spectral sensitivities of visible colour and colour infrared film

a. Colour Film



b. Colour Infrared Film



Source: Harrison and Jupp (1989) Figure 14

A4.2 Aerial Photography

The spatial resolution of aerial photography is determined by the combined effects of film grain, camera optics and flying height. The scale of aerial photography may be determined by dividing the focal length of the camera by the vertical height of the lens above ground level (see Figure A4.3):

$$S = \frac{f}{H - h}$$

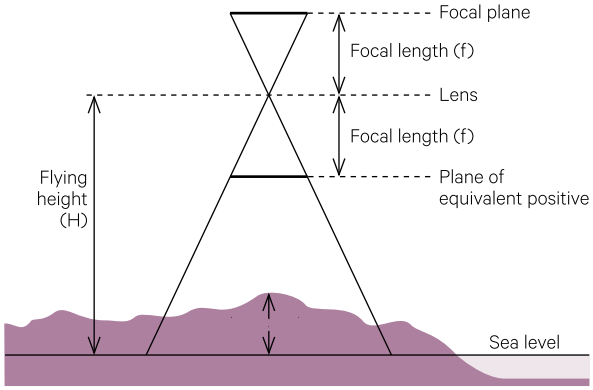
where

S is the scale;
f is the focal length;
H is the flying height; and
h is the terrain elevation.

If these parameters are unknown, the scale may also be computed by dividing the distance between two points on the photograph by the ground distance separating them. In either case, the units used to measure these parameter pairs must be consistent. The resulting scale is generally referenced as a fraction (e.g. 1/25,000) or ratio (e.g. 1:25,000).

Since photographic devices can only directly detect radiation in the visible and near infrared range of the EM spectrum, the resulting data are affected by cloud cover. Photographic imagery may also be produced for other wavelength regions using film-recording techniques after the radiation has been initially recorded by appropriate sensors. The range of processing options available for photographic imagery (without digitising) is greatly reduced compared with the range for digital imagery.

Figure A4.3 Photographic scale



Remote sensing devices that record data photographically require that the film be recoverable for processing. Such devices have been carried by manned and unmanned aircraft, or retrievable spacecraft (such as the Space Shuttle). Examples of data collected this way include traditional aerial photography, the Large Format Space Camera imagery and Shuttle Imaging Radar scenes.

Interpretation of photographic imagery has traditionally relied heavily on the skills and time of a trained human interpreter. Tools for photointerpretation include colour or tone, texture, patterns, shapes, shadows, as well as feature size and situation. Photographic data may be converted into a digital image via the digitising process described in Appendix 4.3.

More recently, digital cameras are used in preference to film cameras. These ubiquitous devices are becoming ever cheaper, smaller and more powerful. At the top end of the range, gigapixel cameras acquire very high spatial resolution imagery for a range of applications, including Earth Observation (EO).

A4.3 The Digitising Process

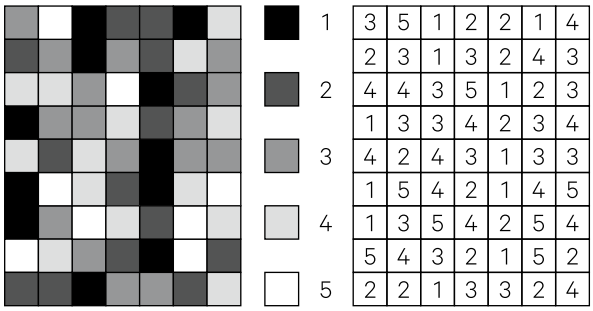
Any picture, photograph or map can be digitised. Automatic scanning devices, which operate in a similar manner to the satellite scanning systems, can be used to convert coloured or black and white maps, pictures or photographs, into digital images for processing by computer.

The conversion of an image from pictorial to 'raster' format is called scan digitising (as opposed to line digitising), and involves two basic processes:

- Sub-divide the image using a grid (or some other systematic tessellation) pattern into small cells called picture elements or pixels. Obviously, a finer digitising grid will produce a digital image with greater spatial detail but also with a larger number of pixels.
- Assign a single numeric value to each pixel to represent its overall brightness level. When a number has been assigned to every pixel, the image is represented by a two-dimensional integer array as shown in Figure A4.4.

Figure A4.4 A digital image

The 'colour' of each grid cell is represented by a number



3	5	1	2	2	1	4
2	3	1	3	2	4	3
4	4	3	5	1	2	3
1	3	3	4	2	3	4
4	2	4	3	1	3	3
1	5	4	2	1	4	5
1	3	5	4	2	5	4
5	4	3	2	1	5	2
2	2	1	3	3	2	4

Source: Harrison and Jupp (1989) Figure 15

A colour image is scanned into three channels, with each channel representing one of the primary colours: blue, green and red. It is possible to recombine several (usually three) registered image channels through a colour additive technique (see Figure 13.2) to generate a colour composite image. The specific colours thus regenerated depend on the grey level patterns in each individual image channel and on the colour filters used in the additive process. Those colour renditions that simulate the original scene colours are called natural colour images; those consisting of significantly different colours to the original scene are referred to as false colour images. The digital image and its processing is further discussed in Volume 2. While the scan digitising process is usually automated, with the grid size being quite small and very subtle changes in colour being recorded as different digital values, the process could be simulated manually for simplified maps.

A4.4 Further Information

Digital Photography Fundamentals: *https://manuals.info.apple.com/MANUALS/0/MA123/en_US/Aperture_Photography_Fundamentals.pdf*

A4.5 References

Harrison, B.A., and Jupp, D.L.B. (1989). Introduction to Remotely Sensed data. Part ONE of the microBRIAN Resource Manual. CSIRO Australia, Melbourne.

Sardar, A.M. (1997) Chronology of the development of remote sensing technology. *Asian-Pacific Remote Sensing and GIS Journal* 2, 35–49.

Appendix 5 Measuring Reflectance

Source: Jupp (1997) *Issues in Reflectance Measurement. CSIRO Earth Observation Centre, Canberra.*

Remote sensors and field instruments used to calibrate and/or validate remotely sensed data measure spectral bands of radiation entering across the field of view of one of a number of instruments. In order that there be a fundamental consistency between such measurements it is important that the instruments be cross calibrated when they are measuring similar information and that enough information be collected for the data to be interpretable and relatable to the eventual application taking them serves.

The measurements are of three basic types:

- radiance;
- irradiance; and
- reflectance.

Provided that basic measurements are consistent and the relationships between radiance and irradiance taken into account, the most important area of concern for us will be the consistent definition and derivation of reflectance factors. It is important to realise that, in practice, there will be a number of ways of defining these, that they will normally not be independent of the conditions under which they are measured and the inter-relationship between different measurements will be complex. Many of these differences arise from the geometry of reflectance measurements and Nicodemus *et al.* (1977) contains probably the most extensive classification of possible geometries.

A5.1 Radiance and Irradiance

The radiance of a source or target is the radiant flux per unit solid angle per unit area normal to the source. It is denoted L and is the quantity to which a narrow angle radiometer is calibrated. Laboratory calibration consists of reading a target of known radiance characteristics as the calibration. However, in practice, calibration in a field setting is also usually needed as the object of the exercise is field measurement.

The reason that the laboratory source is not enough is that when instruments read in a broad band and over a finite Instantaneous Field of View (IFOV) the calibration depends on the wavelength distribution and heterogeneity of the incident source. Hence, calibration in the field setting allows the types of irradiance relevant to the application to be sampled as well as standard laboratory sources.

Irradiance is the total hemispherical radiant flux per unit area and for a radiance distribution, $L(\mu)$, at a specific wavelength irradiating a flat target surface, the resulting irradiance, E, is:

$$E = \int_{2\pi} L(\mu)\cos\theta \, d\omega$$

$$= \int_{0}^{2\pi}\int_{0}^{\frac{\pi}{2}} L(\mu)\cos\theta \sin\theta \, d\theta \, d\phi$$

where

θ, ϕ are the coordinates (zenith, azimuth) of the radiance;

μ is a symbol denoting the direction cosines of the direction vector;

ω is solid angle (steradians).

Background image: This Landsat-5 image of Eyre Creek, about 100 km north of Lake Eyre, was acquired on 28 March 2011. Lake Eyre, located in northern SA, is the largest, driest and lowest salt lake in Australia. This image (displayed using bands 2, 4, 5 as RGB) captures this arid region after a rare rainfall event.
Source: Norman Mueller, Geoscience Australia

If the irradiance distribution (such as a sky distribution) were a constant radiance at all points of the hemisphere (L) independent of angle, it would follow that:

$$E = L\int_{2\pi} \cos\theta \, d\omega$$
$$= L\int_0^{2\pi}\int_0^{\frac{\pi}{2}} \cos\theta \sin\theta \, d\theta \, d\phi$$
$$= \pi L$$

Later, another irradiance definition will be briefly mentioned. It is the scalar irradiance which measures the total incident radiant flux rather than the normal incident radiant flux. It will be denoted here as S and is:

$$S = \int_{2\pi} L(\mu) d\omega$$
$$= \int_0^{2\pi}\int_0^{\frac{\pi}{2}} L(\mu) \sin\theta \, d\theta \, d\phi$$

For a constant radiance distribution (L) it follows that:

$$S = L\int_{2\pi} d\omega$$
$$= L\int_0^{2\pi}\int_0^{\frac{\pi}{2}} \sin\theta \, d\theta \, d\phi$$
$$= 2\pi L$$

The ratio of the normal irradiance to the scalar irradiance is a measure of the angular distribution of the radiance. It is sometimes called the 'average cosine' of the field.

$$\overline{\mu} = \frac{E}{S} = \frac{\int_{2\pi} L(\mu) \cos\theta \, d\omega}{\int_{2\pi} L(\mu) d\omega}$$
$$= \frac{\int_0^{2\pi}\int_0^{\frac{\pi}{2}} L(\mu) \cos\theta \sin\theta \, d\theta \, d\phi}{\int_0^{2\pi}\int_0^{\frac{\pi}{2}} L(\mu) \sin\theta \, d\theta \, d\phi}$$

For a uniform distribution of radiance the value of $\overline{\mu}$ is 0.5.

A5.2 Reflectance

The reflectance factor we measure in the laboratory and field is generally one of two types. There is the directional reflectance factor, ρ_t:

$$\rho_t = \frac{\pi L_t(\mu_r)}{E_d}$$

This measurement is the target radiance recorded by the observer in the 'reflected' direction (μ_r) multiplied by π and divided by the total irradiance on the target (E_d). The directional reflectance factor is the factor closest to what is normally produced by atmospheric correction of remotely sensed data and measured in the field with a narrow IFOV radiometer.

A second measured reflectance factor is the irradiance reflectance:

$$R = \frac{E_u}{E_d}$$

This is the ratio of upwelling irradiance to downwelling irradiance and it is the reflectance factor obtained with an integrating sphere or from the ratio of data taken by cosine collecting diffusers in field experiments. It is sometimes called the spectral 'albedo' (Strahler *et al.*, 1995) although the above definition is for a particular wavelength and the albedo of energy balance studies is the ratio of total irradiances over all (shortwave) bands. The irradiance reflectance is measured by a LI-COR instrument in water studies and by an integrating sphere in the laboratory.

There are two complications to be taken into account in practice which will be revisited later. The definitions so far relate to radiances in specific directions in elements of solid angle $d\omega$ and at a single wavelength. All of the instruments we are concerned with measure over finite wavebands and over finite solid angles and the broader these bands and angles are, the further the resulting reflectance factors will diverge from the ones we have so far defined.

A5.3 BRDF and reflectance functions

The BRDF, or Bidirectional Reflectance Distribution Function, $f\left(\mu_r,\mu_i\right)$, is not a reflectance but a 'kernel' or 'phase function' relating incoming and outgoing radiance. The (reflected) radiance observed in the observer direction, $L_r\left(\mu_r\right)$, is the composite of radiances derived from the incident (sky and Sun for field measurements) radiance distribution, $L_i\left(\mu_i\right)$:

$$L_r\left(\mu_r\right)=\int_{2\pi} f\left(\mu_r,\mu_i\right)L_i\left(\mu_i\right)\cos\theta_i\, d\omega_i$$

$$=\int_0^{2\pi}\int_0^{\frac{\pi}{2}} f\left(\mu_r,\mu_i\right)L_i\left(\mu_i\right)\cos\theta_i\sin\theta_i\, d\theta_i\, d\phi_i$$

The BRDF is generally taken as the material property on which the various reflectance factors and other measures can be based.

A5.3.1 Directional reflectance factor

The reflectance measured as the directional reflectance factor, ρ_t, is therefore expressed in terms of the BRDF as:

$$\rho_t=\frac{\pi L_r\left(\mu_r\right)}{E_d}$$

$$=\pi\frac{\int_0^{2\pi}\int_0^{\frac{\pi}{2}} f\left(\mu_r,\mu_i\right)L_i\left(\mu_i\right)\cos\theta_i\sin\theta_i\, d\theta_i\, d\phi_i}{\int_0^{2\pi}\int_0^{\frac{\pi}{2}} L_i\left(\mu_i\right)\cos\theta_i\sin\theta_i\, d\theta_i\, d\phi_i}$$

$$=\pi\bar{f}\left(\mu_r;E_d\right)$$

where $\bar{f}$ is the BRDF and is an irradiance weighted average BRDF which depends on the irradiance angular distribution of E_d as well as the view direction.

For a uniform radiance distribution (L_i a constant for all directions) the measured reflectance factor would be:

$$\rho_t=\pi\bar{f}\left(\mu_r,2\pi\right)$$

$$=\int_0^{2\pi}\int_0^{\frac{\pi}{2}} f\left(\mu_r,\mu_i\right)\cos\theta_i\sin\theta_i\, d\theta_i\, d\phi_i$$

$$=\bar{\rho}\left(\mu_r,2\pi\right)$$

Where $\bar{\rho}\left(\mu_r,2\pi\right)$ is the directional reflectance factor for a uniform distribution and is a function of the material surface being measured.

For a direct beam irradiance from direction μ_s the measured reflectance factor would be:

$$\rho_t=\pi f\left(\mu_r,\mu_s\right)$$

$$=\bar{\rho}\left(\mu_r,\mu_s\right)$$

where $\bar{\rho}\left(\mu_r,\mu_s\right)$ is often called the BRF or Bidirectional Reflectance Factor for direct beam irradiance. It is also a property of the material and is obviously the BRDF up to the factor π.

A5.3.2 Irradiance reflectance

The irradiance reflectance can also be expressed in terms of the BRDF as:

$$R_t=\frac{E_u}{E_d}$$

$$=\frac{\pi\int_0^{2\pi}\int_0^{\frac{\pi}{2}}\bar{f}\left(2\pi,\mu_i\right)L\left(\mu_i\right)\cos\theta_i\sin\theta_i\, d\theta_i\, d\phi_i}{\int_0^{2\pi}\int_0^{\frac{\pi}{2}} L\left(\mu_i\right)\cos\theta_i\sin\theta_i\, d\theta_i\, d\phi_i}$$

$$=\pi\bar{f}\left(2\pi,E_d\right)$$

$$=\bar{\rho}\left(2\pi,E_d\right)$$

where:

$$\bar{f}\left(2\pi,\mu\right)=\frac{\int_0^{2\pi}\int_0^{\frac{\pi}{2}} f\left(\mu_r,\mu\right)\cos\theta_r\sin\theta\, d\theta_r\, d\phi}{\int_0^{2\pi}\int_0^{\frac{\pi}{2}}\cos\theta_r\sin\theta_r\, d\theta\, d\phi_i}$$

$$=\frac{1}{\pi}\int_0^{2\pi}\int_0^{\frac{\pi}{2}} f\left(\mu_r,\mu\right)\cos\theta_r\sin\theta_r\, d\theta_r\, d\phi_r$$

For a uniform irradiance, it follows that:

$$R_t = \frac{\pi \int_0^{2\pi}\int_0^{\frac{\pi}{2}} \bar{f}\left(2\pi,\mu_i\right)\cos\theta_i \sin\theta_i \, d\theta_i \, d\phi_i}{\int_0^{2\pi}\int_0^{\frac{\pi}{2}} \cos\theta_i \sin\theta_i \, d\theta_i \, d\phi_i}$$

$$= \pi\bar{f}\left(2\pi,2\pi\right)$$

$$= \bar{\rho}\left(2\pi,2\pi\right)$$

This 'Bi-hemispherical Reflectance Factor' (Nicodemus *et al.*, 1977) is another material property directly derived from the BRDF. It is close to the measurement made in the laboratory with an integrating sphere.

In addition, if the irradiance is beam irradiance from direction μ_s it follows that:

$$\bar{\rho}\left(2\pi,\mu_s\right) = \pi\bar{f}\left(2\pi,\mu_s\right)$$

Without pursuing the discussion here, the 'reciprocity' principle implies that:

$$\bar{f}\left(\mu,2\pi\right) = \bar{f}\left(2\pi,\mu\right)$$

hence

$$\bar{\rho}\left(\mu,2\pi\right) = \bar{\rho}\left(2\pi,\mu\right)$$

The objective of processing remotely sensed data to 'reflectances' and measuring 'reflectances' is to establish a property of the materials rather than the environmental conditions. The BRDF is not always only a property of the material but the assumption is normally made that it is 'close' to a material property independent of the radiation environment. The BRDF is also the source for the reciprocity relations. Moreover, the measurable reflectance factors have complex geometrical relationships and depend on the environmental conditions. That is, there can really be no 'spectral library' without a clear record of the measurement geometry, the environmental conditions and sensor all being specified. They are part of the spectrum and the only means by which the different measurements can eventually be compared.

The laboratory based integrating sphere irradiance reflectance and the field directional reflectance factors are different measurements and they depend on the irradiating source and the measurement conditions. However, it is our objective to attempt to get standard measurements and material properties. One way towards this is to define a directional quantity:

$$\gamma\left(\mu_r,\mu_s\right) = \frac{\bar{\rho}\left(\mu_r,\mu_s\right)}{\bar{\rho}\left(2\pi,2\pi\right)}$$

This quantity is a material property and contains essentially the directional behaviour.

A5.3.3 Summary of special cases

The BRF is the reflectance measured by the radiance radiometer when there is only incident beam (e.g. Sun) radiation. To summarise the factors arising from the uniform irradiance distribution case in terms of the BRF:

$$\bar{\rho}\left(\mu_r,2\pi\right) = \frac{1}{\pi}\int_0^{2\pi}\int_0^{\frac{\pi}{2}} \bar{\rho}\left(\mu_r,\mu_i\right)\cos\theta_i \sin\theta_i \, d\theta_i \, d\phi_i$$

$$\bar{\rho}\left(2\pi,\mu_i\right) = \frac{1}{\pi}\int_0^{2\pi}\int_0^{\frac{\pi}{2}} \bar{\rho}\left(\mu_r,\mu_i\right)\cos\theta_r \sin\theta_r \, d\theta_r \, d\phi_r$$

$$= \bar{\rho}\left(\mu_i,2\pi\right)$$

$$\bar{\rho}\left(2\pi,2\pi\right) = \frac{1}{\pi}\int_0^{2\pi}\int_0^{\frac{\pi}{2}} \bar{\rho}\left(2\pi,\mu_i\right)\cos\theta_i \sin\theta_i \, d\theta_i \, d\phi_i$$

$$= \frac{1}{\pi}\int_0^{2\pi}\int_0^{\frac{\pi}{2}} \bar{\rho}\left(\mu_r,2\pi\right)\cos\theta_r \sin\theta_r \, d\theta_r \, d\phi_r$$

In Strahler *et al.* (1995), $\bar{\rho}\left(2\pi,\mu_i\right)$ is called the 'Black Sky' Albedo and $\bar{\rho}\left(2\pi,2\pi\right)$ is called the 'White Sky' Albedo. Estimates of these quantities will be standard products from MODIS expressed as polynomial functions. Some simplification of these expressions is also possible if it is assumed the BRDF is symmetrical relative to the Principal Plane and the integrations with respect to ϕ changed to azimuthal difference.

A5.4 Natural Radiation Measurements

The natural light irradiance that is measured by a well calibrated device with a good cosine response has a primary atmospheric component (E_d) that can be expressed as:

$$E_d = E_0' \cos\theta_s t_s + \int_0^{2\pi}\int_0^{\frac{\pi}{2}} L_{sky}\left(\mu_i\right)\cos\theta \sin\theta \, d\theta \, d\phi$$
$$= E_{dir} + E_{diff}$$

where

E_0' is the exoatmospheric normal irradiance (corrected for Sun-Earth geometry);
t_s is the beam transmittance;
L_{sky} is the sky radiance distribution from the upper hemisphere;
E_{dir} is the direct irradiance; and
E_{diff} is the diffuse irradiance.

The ratio of the diffuse term E_{diff} to the total E_d is the fraction of diffuse radiation:

$$f_d = \frac{E_{diff}}{E_d}$$

Strictly, these expressions are for a 'black' Earth but in practice, there are interactions between the Earth and sky which are greatest when the diffuse fraction is high. Radiation reflected back into the atmosphere from the Earth is again reflected back to the surface by an atmospheric reflectance(s). This means that the measured irradiance can be expressed as:

$$E_d^* = \frac{E_d}{1 - s\rho^*}$$

where ρ^* is the local background reflectance near the target which is approximately an average over an area of about 200 metres radius under some conditions and s depends on the atmospheric turbidity. The effects due to s are smallest for clear skies (when the diffuse radiation is low) and highest when the atmospheric turbidity is high (when the diffuse radiation is high).

In practice, the increase in irradiance can be regarded as a component of the (even more diffuse) diffuse sky distribution.

$$E_d^* = E_{dir} + E_{diff}^*$$
$$= E_{dir} + \frac{s\rho^* E_{dir} + E_{diff}}{1 - s\rho^*}$$

and

$$f_d^* = f_d + \left(1 - f_d\right) s\rho^*$$

It is important to recognise the presence of the background effect (which becomes most significant in atmospheric correction) by always assessing and (if possible) measuring the background as part of a target field survey. Because of this extra term, it is often not possible to neglect the effect of the diffuse fraction outlined here, especially in the near infra-red when the background is green.

If the irradiance distribution is modelled simply as a beam term (the direct radiation) and a uniformly diffuse irradiance term (assuming a uniform sky radiance distribution), it follows that the measured reflectance factors will be:

$$\rho_t = \left(1 - f_d\right)\bar{\rho}\left(\mu_r, \mu_s\right) + f_d \bar{\rho}\left(\mu_r, 2\pi\right)$$
$$R_t = \left(1 - f_d\right)\bar{\rho}\left(2\pi, \mu_s\right) + f_d \bar{\rho}\left(2\pi, 2\pi\right)$$

In this expression there are the three special case material property measures and the fraction of diffuse radiation at the wavelength being measured. This gives a lead as to how field measurements may be done to estimate the BRDF. A range of measurements could taken under natural conditions (where diffuse and direct irradiance terms are measured) with (possibly) both directional and irradiance reflectances measured. If the BRDF is modelled with a parametric model, the parameters could be chosen to fit the data.

Using the directional term defined previously, these equations may be written:

$$\rho_t = \bar{\rho}\left(2\pi, 2\pi\right)\left(\left(1 - f_d\right)\gamma\left(\mu_r, \mu_s\right) + f_d \gamma\left(\mu_r, 2\pi\right)\right)$$
$$R_t = \bar{\rho}\left(2\pi, 2\pi\right)\left(\left(1 - f_d\right)\gamma\left(2\pi, \mu_s\right) + f_d\right)$$

It would be ideal if from such field data and other sources (such as airborne data) some relatively consistent γ functions were found for classes of land cover. It may be necessary to use different functions (that is, 'kernels') for the different covers but the key is to have some consistency in the γ functions.

A5.5 Measuring Reflectance in the Field

In principle, if a calibrated instrument measured the radiance and another the irradiance the reflectance could be computed simply as:

$$L_t = \frac{1}{\pi}\rho_t E_d^*$$

$$\rho_t = \frac{\pi L_t}{E_d^*}$$

This is the paired radiometer approach and the operation of atmospheric correction of remotely sensed data effectively works in this same way.

However, in the field there is an alternative and very convenient way to measure the reflectance without separately measuring the irradiance which uses a *reflectance standard*. It can easily be carried out with a single instrument plus a panel rather than two instruments.

A reflectance standard is a panel of known total and directional reflectance properties. If the target radiance (L_t) is measured by a radiance radiometer and the standard radiance (L_s) is also measured under the same geometrical and environmental conditions with the same instrument then, if ρ_s is the known reflectance of the standard it follows that:

$$\rho_t\left(\mu_r, E_d\right) = \frac{\pi L_t\left(\mu_r\right)}{E_d}$$

$$\rho_s\left(\mu_r, E_d\right) = \frac{\pi L_s\left(\mu_r\right)}{E_d}$$

$$\rho_t\left(\mu_r, E_d\right) = \rho_s\left(\mu_r, E_d\right)\frac{L_t\left(\mu_r\right)}{L_s\left(\mu_r\right)}$$

Moreover, suppose the calibration relation between volts measured by the instrument measuring the radiance (with dark current effect removed) and radiance is linear and can be written as:

$$L = c_L V$$

it then follows that the reflectance of the target (t) can be obtained without knowing c as:

$$\rho_t\left(\mu_r, E_d\right) = \rho_s\left(\mu_r, E_d\right)\frac{V_t}{V_s}$$

In this expression, only the properties of the standard must be known other than the uncalibrated target and standard readings.

Note that in the case of the paired radiometers it follows that:

$$\rho_t = \frac{\pi c_L}{c_E}\frac{V_t}{V_d}$$

That is, the ratio of the instrument calibration factors must be known and be stable. However, for expensive instruments the use of paired radiometers is often not an option and only the panel method is feasible.

It is convenient to write the reflectance of the standard panel in the form:

$$\rho_t\left(\mu_r, E_d\right) = R_s K_s\left(\mu_r, \mu_s, f_d; \lambda\right)$$

where R_s is the Bi-hemispherical reflectance of the panel (as measured, for example by an integrating sphere) and K_s is the panel K-factor. It is shown as a function of observer position, Sun position, fraction of diffuse irradiance and wavelength as all of these can affect it.

In terms of modelling the panel BRDF it is useful to consider the simplified irradiance model of direct plus uniform diffuse for which:

$$\begin{aligned}\rho_s\left(\mu_r, E_d\right) &= \left(1-f_d\right)\bar{\rho}\left(\mu_r, \mu_s\right) + f_d\,\bar{\rho}\left(\mu_r, 2\pi\right)\\ &= \bar{\rho}\left(2\pi, 2\pi\right)\left(\left(1-f_d\right)\gamma\left(\mu_r, \mu_s\right) + f_d\,\gamma\left(\mu_r, 2\pi\right)\right)\\ &= R_s K_s\left(\mu_r, \mu_s, f_d; \lambda\right)\end{aligned}$$

That is, the panel could be characterised by its directional function and its Bi-hemispherical Reflectance Factor and K obviously depends on both the Sun and observer positions as well as f_d in the field if there is a significant BRDF variation.

At this point, without going too far with the (very wide) discussion, it is necessary to remember that the panel method discussed here assumes that the panel essentially 'replaces' the target to get the reference measurement. If the target and standard are separated then the measured reflectance factor will be different again from the ones being considered. There are many cases where panel and target are in quite different situations. These provide us with equally different 'reflectance' measurements.

A5.5.1 Establishing K-factor panels

A considerable amount of attention is normally given to making a standard panel close to a 'Lambertian' target. A Lambertian target is perfectly diffusing and has uniform BRDF over the outgoing hemisphere. For a truly Lambertian panel, therefore K_s is 1.0 and only R_s needs to be known. Since a Lambertian panel is difficult to approximate, the panel K-factor must be carefully assessed. Low Sun, specular panel effects and diffuse conditions will create problems if K_s is ignored.

Normally, considerable work is expended on a basic standard panel or money expended to buy a standard panel for the laboratory. These are often quite small and not field-robust. For field missions, the panels normally need to be large and robust as well as able to be cleaned. These requirements often mean they do not have ideal Lambertian behaviour and may change with use. Hence, establishing the panel K-factor and monitoring it is a basic step in field procedure.

The first factor needed is R_s which can be measured using an integrating sphere acting on a piece of the panel. This may only need to be done once - it is a normalising factor.

The panel directional factor could be established in the laboratory by physical measurement. Some investigations of this are needed for the larger field standards but this would be normally the way the 'Lambertian' panel is checked. In the past, people have also attempted to carry out some K-factor estimation of a field panel using the near 'Lambertian' panel and natural light as follows:

- assume that the Laboratory panel is Lambertian and has a spectral reflectance which is a constant R_s in the visible NIR range.
- monitor the radiance of the Laboratory standard and the field panel with a narrow FOV radiance sensor at the same time as monitoring the irradiance using a calibrated irradiance sensor with high spectral resolution.
- monitor the diffuse radiation well as total irradiance.
- collect the data over a number of days, with as wide a variation in Sun positions and view angles as possible.

A set of measurements of this type can be used in a number of ways. One important use is to establish Calibration Consistency. That is, if the sensor being used is calibrated then the following equation needs to be consistent when the Laboratory standard is being measured:

$$L_s\left(\mu_r\right)=\frac{1}{\pi}R_s E_d$$

Since the Lambertian panel reflectance (R_s) is assumed known and E_d is measured, this provides a consistency check on the (inter-)calibrations over a wide range of conditions. Departures from a simple calibration can be expected and this will provide an average 'field' corrected calibration of considerable usefulness.

The field (or 'alternate') panel K-factors can be estimated from the data (assuming the Laboratory panel's K-factor is known and the alternate panel Bi-hemispherical Reflectance Factor has been measured using an integrating sphere) by:

$$K_{alt}\left(\mu_r,\mu_s,f_d;\lambda\right)=\frac{\rho_s}{R_{alt}}\frac{V_{alt}}{V_s}$$
$$=\frac{R_s}{R_{alt}}\frac{V_{alt}}{V_s}K_s\left(\mu_r,\mu_s,f_d;\lambda\right)$$

In this way, the estimated K_{alt} will be measured over many conditions of Sun and observer position and environmental conditions if K_s is known. It is very important to measure the azimuthal variation fully to establish specular effects.

However, even with considerable work, the range of measurements is likely to be limited and not cover the range expected in the field. To overcome this, the best strategy would seem to be to fit the K-factor by a parametric function (which is likely to be much simpler for a panel than a natural surface!). For example, a good candidate might be the 'Walthall model' (Walthall *et al.*, 1985; Strahler *et al.*, 1995).

$$\bar{\rho}\left(\mu_r,\mu_i\right)=p_0\left(\theta_r^{\,2}+\theta_i^{\,2}\right)+p_1\theta_r^{\,2}\theta_i^{\,2}+p_2\theta_r\theta_i\cos\phi+p_3$$

The simplifying assumption of uniformly diffuse sky radiation can additionally be used to provide the model for K (since the γ functions will be computable as rational functions of the parameters):

$$K_s\left(\mu_r,\mu_s,f_d;\lambda\right)=\left(1-f_d\right)\gamma\left(\mu_r,\mu_s\right)+f_d\gamma\left(\mu_r,2\pi\right)$$

In this way, a fairly robust panel 'calibration' would be available that can be used under a wide range of conditions.

If such K-factors are established for the panels and tested relative to good laboratory standards then they can then also provide field checks of radiometer calibration against field robust but accurately calibrated irradiance devices. That is if the panel is read and converted to radiance and the irradiance taken at the same time, the following consistency equation should hold:

$$L_s\left(\mu_r\right)=\frac{1}{\pi}R_sK_s\left(\mu_r,\mu_s,f_d;\lambda\right)E_d$$

Readings under a number of conditions with panel radiance, total irradiance and diffuse irradiance measured can supply a constant check of instrument and/or panel behaviour.

In the field, if a panel model of this kind has been developed, the Sun and view positions as well as the fraction of diffuse at the wavelengths used are necessary data in the measurement set as well as the two target and panel readings and data on sky conditions, surrounding area reflectance ideally should be recorded as well.

A5.5.2 Measuring diffuse radiation

Separating diffuse and direct components of the irradiance is essential in most modelling. At very least, the fraction of diffuse should be established when BRDF effects are strong. Diffuse radiation is generated by many sources. Scattering by air and aerosols is a primary source but high objects on the land surface and clouds generate scattered radiation as well and the sky re-reflects radiation leaving the land back into the diffuse term. Clouds are an especially difficult source to model and take into account in corrections.

Therefore, diffuse radiation measurements should be accompanied by descriptions of the site (trees, buildings etc) and the sky (cloud type and amount) for reference. Given such data, the field crew could obtain diffuse data from two setups:

- shadow band instrument; and
- Sun disk shading a LI-COR irradiance sensor or a Spectron with diffuser.

To get diffuse readings using a Sun disk, the procedure is as follows:

1. Have a Sun disk 10 cm diameter and blackened on a thin stick about 50 cm length.
2. Person using disk should stand on the opposite side of the instrument from the Sun and hold the disk 1 m from the sensor head with the shadow centred on the sensor.
3. Take four readings (the Qin Yi method). One reading with no disk and no person, one reading with person in place but disk not used, one reading with person in place and shading the sensor head and lastly one with no person and no disk to see that there has not been significant change.

The person shading the sensor should wear matt clothes which are not too reflective. Note, denim is bright in the near infrared!

If the four readings in 3. above are denoted $\left[E_1,E_2,E_3,E_4\right]$ then the quantities needed are derived as:

$$E_d^*=E_1$$
$$E_{dir}=E_2-E_3$$
$$E_{diff}^*=E_d^*-E_{dir}$$
$$E_4\approx E_1$$

The shadow band method is automatic and much better in principle than the Sun disk. However, the current YES MFR instrument that CL&W and CAR use only records in a relatively few (6) bands and does not therefore provide a complete irradiance description. It may be possible to fit an atmospheric model to the MFR data and predict the irradiance and the fraction of diffuse for the full spectrum. This needs some testing.

To provide some measure of the uniformity of the sky distribution, it may be useful to consider the benefit of taking scalar irradiance data (*S*) as well as cosine irradiance data (*E*). If the Sun disk is used so that the diffuse and direct fraction are know it follows that the average cosine of the complete Sun and sky distribution would be:

$$\bar{\mu}=\frac{E}{S}$$

For no diffuse irradiance:

$$\bar{\mu}=\cos\theta_s$$

If there were significant diffuse radiation but not completely diffuse conditions, a Sun-corrected average cosine for the sky distribution would be:

$$\bar{\mu}_{diff}=\frac{E_{diff}}{S_{diff}}$$
$$=\frac{E-E_{dir}}{S-E_{dir}/\cos\theta_s}$$
$$=\frac{f_d\bar{\mu}}{1-\left(1-f_d\right)\bar{\mu}\cos\theta_s}$$

This can be used to assess the usefulness of the simplified irradiance assumption (that diffuse irradiance is uniform) and also provides useful (phase) data for an atmospheric model when conditions are relatively clear.

A5.6 Summary

This brief outline of the issues needing to be addressed in measurement and modelling of image 'reflectance' given the fact of BRDF and the variety of possible choices for reflectance factors has assumed a single wavelength and that the radiance measurements are done with a narrow Field of View instrument. If either of these assumptions is changed the nature of the measurement also changes.

Provided, however, that the BRDF characteristics of targets or panels are relatively the same over the wavebands of interest and that the targets are relatively homogeneous over the FOV (which should at least be less than or equal to 5° in field measurements) the method and ideas discussed here can be retained. However, any data taken must be augmented with waveband and FOV information.

Given this, the main outcome of the discussion is to suggest that field panels need to be modelled and their K-factors assessed regularly. This is as important as cross calibrating instruments. In addition, if no account is taken of BRDF then there will be wide variations between field and image estimates of reflectance. Spectral libraries may not be possible. Even if very standard viewing geometry is used, the variation of the data with Sun position may be very large.

The issues discussed have ramifications for correction for BRDF in both Atmospheric Correction and field studies. A possible option is to use the simple model:

$$\begin{aligned}\rho_t &= \bar{\rho}\left(2\pi,2\pi\right)\left(\left(1-f_d\right)\gamma\left(\mu_r,\mu_s\right)+f_d\gamma\left(\mu_r,2\pi\right)\right)\\ &= \bar{\rho}\left(2\pi,2\pi\right)\Gamma\left(\mu_r,\mu_s,f_d\right)\end{aligned}$$

Since, if a simple parametric form is available for the BRDF and the diffuse fraction is known it follows that Γ is known and it could be proposed that all measurements be normalised to an apparent Bi-hemispherical Reflectance Factor:

$$\bar{\rho}\left(2\pi,2\pi\right)=\frac{\rho_t}{\Gamma\left(\mu_r,\mu_s,f_d\right)}$$

If the BRDF directional behaviour parameters are defined for a given land cover it may be possible, provided f_d is measured or modelled, to normalise reflectances to the Bi-hemispherical Reflectance Factor in both field situations and in atmospheric correction.

Following from this is a specification for the structure of an adequate Spectral Library. A 'library' entry would include:

1. Waveband and FOV:
   - 1.1 ρ_t (the actual data)
   - 1.2 $\bar{\rho}\left(2\pi,2\pi\right)$
   - 1.3 $\gamma\left(\mu_r,\mu_s\right)$ as a parametric function or land cover 'type'
2. μ_r,μ_s,f_d at the time of the measurement
3. Panel/Target geometry
   - 3.1 ρ^* and other environmental information

Since this allows the original data to be reconstructed, the entry should also include the error of re-construction via the model.

A5.7 References

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