Practical methodologies for the reflectance calibration of *casi* data

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Abstract: *casi* data are routinely provided in units that are directly related to spectral radiance, but for many purposes it is necessary to convert these data to reflectance. There are several methods to achieve this, which vary in their complexity, accuracy, and requirements for resources. This paper reviews two practical methodologies for the conversion of *casi* radiance data to reflectance. The first is based on the use of the Incident Light Sensor (ILS) fitted to the roof of the aircraft. The second uses ground calibration targets of known, stable reflectance.

1. Introduction

Increasingly, users are requiring calibrated data from remote sensing systems. At its simplest, radiometric calibration provides a relationship, usually linear, between digital number value (DN) and spectral radiance. This is sufficient for many purposes, as it means that data from different sensors, or from different spectral bands of the same sensor can be compared. Failure to specify even this lowest level calibration risks introducing errors into even the simplest analyses (Crippen, 1988). However, for many purposes, especially those involving the study of change through time, or those focusing on dark targets or those in which physical data are important, it is necessary to go beyond this basic radiometric calibration. In such cases, it is also necessary for the influence of the atmosphere to be removed, and it may also be desirable for the radiance values to be converted to reflectance, which is a intrinsic property of the surface and is independent of the illumination and atmospheric conditions at the time of measurement. Even this is not the ultimate goal, as the reflectance of natural surfaces varies as a function of the illumination and view geometry, and therefore the long-term goal should be the retrieval of the bi-directional reflectance factor, which is the physical manifestation of the bidirectional reflectance distribution function (BRDF).

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There are a number of methods to account for the influence of illumination and the atmosphere on sensor recorded radiance including; (i) normalisation to a spectrally flat target or an image average (Ben-Dor *et al*., 1994), (ii) empirical relationships between radiance (or DN) and reflectance (Milton and Webb, 1987), (iii) radiative transfer models to simulate the interaction of radiation with the atmosphere and the surface (Kneizys, *et al*., 1980) and (iv) multi-height or multi-angle observations (Steven and Rollin, 1986). The performance of these different methods have been compared by a number of authors (e.g. Roberts *et al.* 1986; Farrand *et al.* 1993; Clark *et al*., 1993; Dwyer *et al.* 1995; Ferrier 1995) and generally the most accurate results have been found to come from the combination of a radiative transfer model with a few ground targets of known reflectance, referred to as the 'radiative transfer ground calibrated' (RTGC) method (Clark *et al*., 1999).

Clark *et al*. (1999) estimate that the calibration of AVIRIS data for one site involves 1 to 2 person months using the RTGC method. Such high levels of accuracy are not always required or justified in terms of the cost of data processing or the cost of ancillary data. This paper investigates simpler, empirical methods of reflectance calibration, which achieve many of the advantages of the full methods, but are considerably more practical to achieve operationally. The paper will focus on the Itres Instruments Compact Airborne Spectrographic Imager (*casi*), as flown by the UK Natural Environment Research Council and the UK Environment Agency. This sensor provides data which are calibrated to radiance in the manner described by Riedmann and Rollin (this conference), leaving the user to concentrate on atmospheric correction and conversion to reflectance.

2. Irradiance-based methods of reflectance calibration

The first approach to reflectance calibration is to have some means of measuring the irradiance on the target at the instant the radiance is measured by the *casi*. This may be achieved either by having a spectroradiometer (or sunphotometer) at a fixed ground location within the survey area or by having a similar instrument mounted on the roof of the aircraft. The first method achieves the highest precision for the specific location of the spectroradiometer, but is unable to account for the spatial variation of the atmosphere over the whole area surveyed. The 'patchiness' of water vapour is well-established (Steven and Rollin, 1986; Gao *et al*., 1991) and thus a method which provides a spatially distributed atmospheric correction is desirable, even if it does not produce a correction for every pixel in the image. The second method provides data for every line in the image but is unable to account for the column of atmosphere below the aircraft where most of the water vapour and particulate matter is likely to be concentrated. The *casi* instrument has an 'Incident Light Sensor (ILS)' fitted to the roof of the aircraft which provides a line-by-line measurement of the spectral irradiance, and so in this paper attention will focused on this approach, which will be termed the 'ILS method'.

2.1 Investigation of the ILS method under controlled conditions

In order to test the feasibility of using a roof-mounted sensor to measure irradiance, and experiment was performed using a Spectron Engineering SE-590 spectroradiometer mounted on a Bell Jet Ranger helicopter. The three-dimensional manoeverability of a helicopter was necessary in order to make repeated measurements over a fixed target and also to maintain a horizontal, stable attitude. The SE-590 was used with two sensor heads, one to measure solar irradiance, the other for target radiance. The upwards pointing sensor head was fitted with a cosine-corrected receptor and attached to a bracket mounted above the cabin which afforded a clear view of a complete hemisphere, obstructed only by the rotor blade assembly.

The SE-590 target head was fitted with a nominal 1° field-of-view lens, and this, together with a 35mm camera and videocamera, was mounted at the end of a support bar which rested across the lap of the rear port-side passenger. The adjacent rear door of the helicopter was taken off completely so that the instruments could view the target through the gap between the cabin body and the landing skid. Two digital inclinometers were mounted on the support bar so as to provide a continuous record of sensor attitude (roll and pitch), alongside a television monitor which was linked to the videocamera. The SE-590 control unit and a data logger connected to the inclinometers were held on the lap of the second rear passenger.

Data were collected over spatially uniform areas of grass and asphalt and further details of the experiment are provided by Milton *et al*. (1994). Five to eight spectra were measured from each site at each of four altitudes: 760m, 550m, 300m and 150m above ground level. Altitude was determined using the helicopter altimeter corrected for the average height of the ground above sea level. Measurements of irradiance were made before and after each set of target scans, which took around 30 seconds to perform. Scans made from the helicopter which were off-target were identified by examining the video footage, and were omitted from further analysis. Likewise, by inspecting the inclinometer data associated with each scan, those measurements made at an angle greater than 5° off-nadir were eliminated.

In order to correct for the reduction in irradiance caused by the rotor blades, the mean reflectance spectrum measured at ground level was ratioed with that measured at 150 metres and a correction file derived which could then be applied to the other helicopter spectra collected at the same time. Safety considerations determined the lowest altitude from which the grass site could be measured, and this meant that the 'rotor chop correction' also took account of atmospheric effects occurring within the lowest 150 metres of the atmosphere. Evidence for the limited extent of atmospheric effect upon the spectrum measured at 150 metres is provided by the absence of absorption features due to water vapour, in contrast to the spectra from higher altitudes discussed later.

Reflectance spectra were produced using 'rotor chop corrected' irradiance data from the upward-looking spectroradiometer and examples of those from 150m and 760m altitude are shown in Figure 1.

These spectra show that it is necessary to take into account the effect of the atmosphere beneath the platform, even at relatively low altitudes (760m) and that the effect of the atmsophere varies with wavelength. Between 400-520nm the apparent reflectance of the grass surface was higher at 760m than at 150m due to the additive effect of path radiance. Above 580nm it was higher at 150m due to absorption in the atmosphere, especially in the water absorption bands around 820nm and 940nm. Interestingly, between 520nm and 580nm, the apparent reflectance was constant with height.

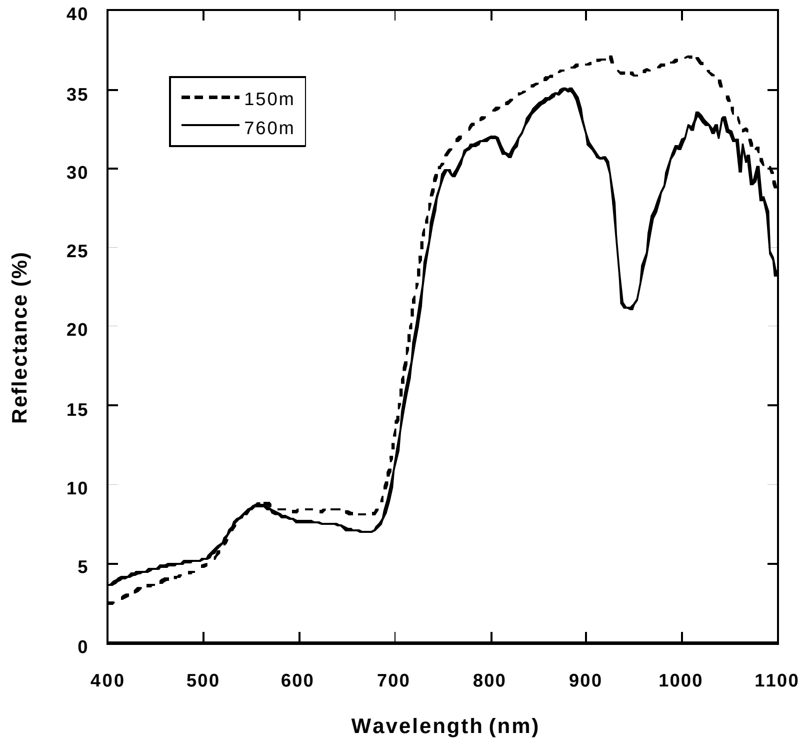


Figure 1: Comparison between apparent reflectance spectra of mown grass measured at 150m and 760 altitude using the ILS method

2.2 Investigation of the ILS method with *casi* data

On 3rd September 1999 the intertidal vegetation bordering the West Solent was surveyed using the Environment Agency *casi* on behalf of English Nature. Over 30 flightlines were flown at an altitude of 2,500 feet between 09:00[2] and 12:40. The *casi* was configured in spatial mode using the intertidal bandset recommended by Thomson *et al*. (1998) and ILS data were recorded in the same wavebands. A Spectron SE-590 spectroradiometer was operated on the ground at a central calibration site and broadband irradiance sensors were installed at two other locations within the study area (Figure 2).

All three irradiance sensors recorded similar trends during the period of the aerial survey, indicating that the atmosphere over the area of interest was spatially uniform. However, the irradiance did change during the time the survey was in progress (Figure 3). Between 09:00 and approximately 10:45 the solar irradiance steadily increased as the early morning mist cleared. Around 11:00 there was an interval during which the solar irradiance changed rapidly as high level clouds passed over the area, but by 11:20 the atmosphere had cleared and was then very stable until at least 12:45.

[2] All times GMT

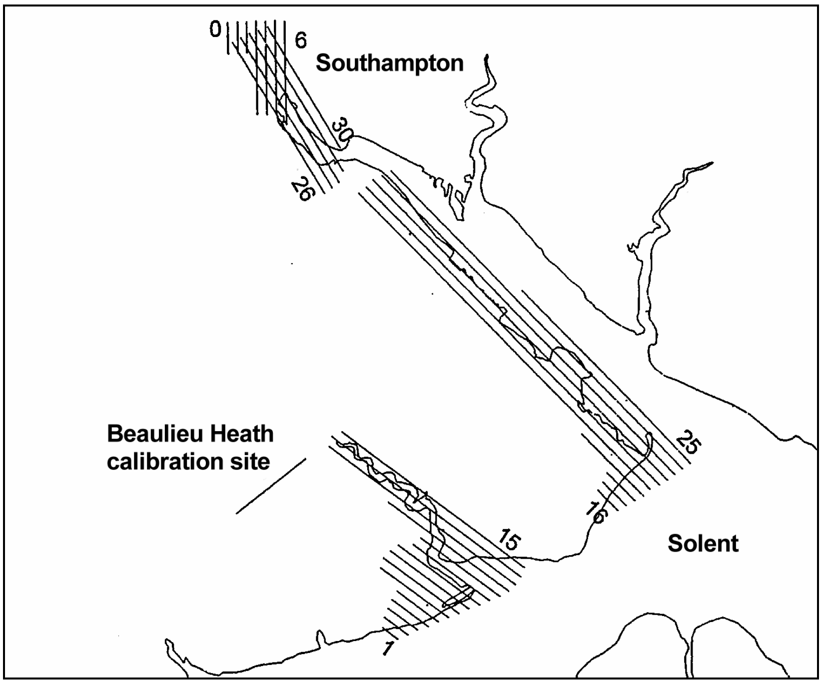


Figure 2: Location map of the *casi* flights used for the ILS test and the Beaulieu Heath calibration site

Data from the *casi* ILS were first screened to exclude those data collected when the roll sensor indicated that the attitude of the aircaft was more than 0.01 degree from the horizontal. Pitch was not recorded by the *casi* system in operation at that time, and the only indication of aircraft yaw was the heading recorded in the flightline logs. The flightline-averaged irradiance data recorded by the ILS are shown on Figure 3 in relation to the irradiance measured at the ground. In this figure the ILS data are categorised according to whether the flightline was ‘into-Sun’ or ‘out of Sun’ and it is evident that the direction of flight had an effect upon the ILS data. This may have been caused by the ILS having an inaccurate cosine response, or by spurious reflections into the ILS from other parts of the airframe.

Other problems encountered with the ILS were low signal-to-noise ratio, especially at short wavelengths due to signal being lost in the optical fibre linking the cosine receptor mounted in the roof of the aircraft to the *casi* instrument. Clearly, the ILS as configured for these flights was not suitable for use as an irradiance sensor to convert the data to reflectance and further work on this aspect was halted pending upgrade to the system by the manufacturers.

An error analysis of the *casi* ILS by Shepherd and Xu (1993) also identified low signal values at the shorter wavelengths as a problem, but they found that the cosine response of the sensor was very good in a laboratory calibration. They concluded that it should be possible to use the *casi* ILS to measure apparent reflectance *at the aircraft* to a precision of better than 5% at wavelengths greater than 500nm. In order to measure the apparent reflectance at the ground it would still be necessary to take account of the atmosphere beneath the aircraft.

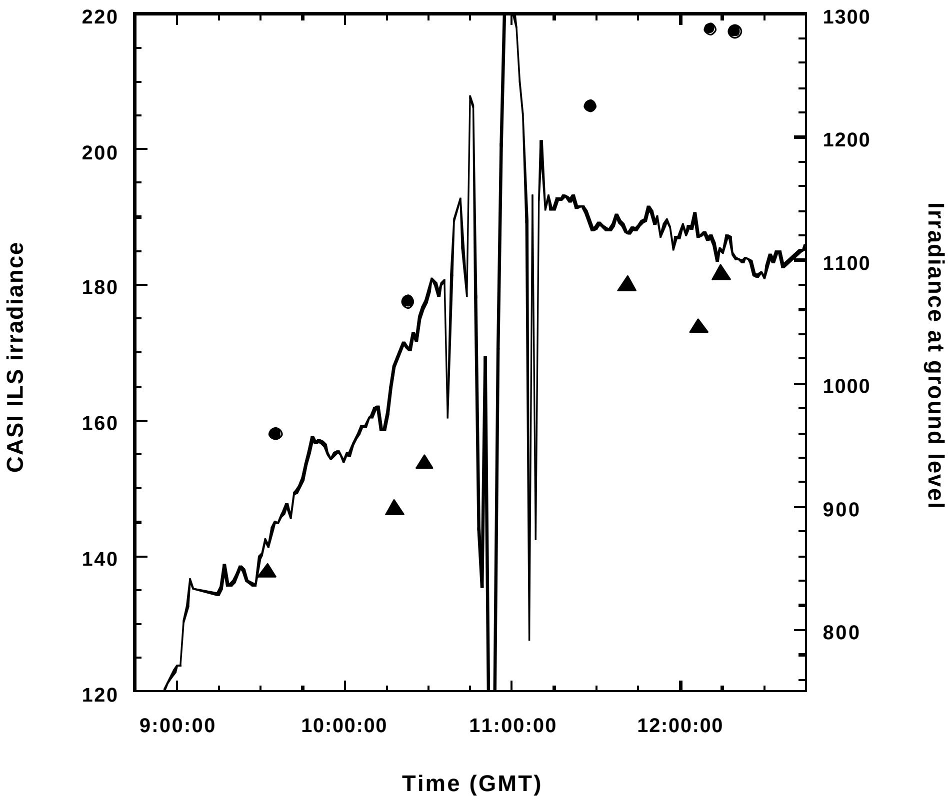


Figure 3: Temporal trend in irradiance during the *casi* flights.
Solid line indicates measurements at ground level. Symbols indicate the flightline-averaged ILS values (roll within 0.01° of horizontal). Flightlines denoted by triangles were flown into the Sun, those by circles were flown away from the Sun.

3. Use of ground targets to calibrate *casi* data to reflectance

Ground targets, either natural or artificial, may be used to calibrate remotely sensed data directly by matching the DN values recorded from the aircraft or satellite sensor with the radiance or reflectance measured on the ground (Slater *et al*., 1987). If radiance is used, the ground data must be measured simultaneously with the remotely sensed data. Reflectance-based calibration is less time-critical, but how much so depends upon the nature of the ground target and the illumination conditions at the time.

3.1 Data normalisation

Schott *et al*. (1988) describe a method to standardise different remotely sensed data sets of the same area which relies on the identification of 'pseudo-invariant features' (PIF) on the image. These are objects on the ground whose mean response in the wavelengths of interest is assumed to be unchanged between the different times of survey. Importantly, the method does not assume that individual pixels are unchanged in response, merely that the overall mean of the class to which they belong has remained stable. Thus an urban area may be identified as a PIF, even though a particular pixel within the urban class is in shadow on one image and in full Sun on another. This approach can be very effective in normalising the response between images but it falls short of true calibration.

3.2 Requirements of a ground target

In order to calibrate an image to reflectance using this approach it is necessary to have physical measurements from the ground targets chosen. The may be radiance or reflectance measurements at the time of sensing, or else reflectance measurements at another time and a quantitative model of how the spectral reflectance of the ground target changes with time.

Clark *et al*. (1999) have published a useful practical guide to this approach to reflectance calibration, largely gained from their own experience with AVIRIS data and the following recommendations are largely drawn from their work. Candidate ground targets must be spatially extensive, both to avoid adjacency effects from surrounding areas (Dana, 1982), and so as to include many ground resolution elements (GRE), thereby reducing the standard error of the mean DN value. They should be spatially uniform, have little or no microrelief and be either horizontal or gently sloping. Calibration targets should be at a similar altitude to the study area. For practical reasons they also need to be accessible, possibly at very short notice, but not so accessible as to encourage unwanted visitors. Ground targets should be chosen with a range of reflectances that bracket those expected from the targets of interest, and they should have fairly 'flat'spectra (i.e. no marked absorption features).

A simple multiband radiometer can be used to test candidate ground targets for their suitability. Typical targets include disused airfield runways, asphalt car parks or the roofs of large buildings. However, even these surfaces can present problems, as when Chavez (1989) found when shoppers parked on the mall car park he proposed to use and Milton *et al*. (1997) found when freshly painted fluorescent markings appeared on the car park they proposed to use. One solution to this problem is to use a remote desert site (e.g White Sands) or to create a dedicated calibration target by clearing an area of ground (e.g. Wu *et al*., 1997) or laying out an artificial canvas or tarpaulin sheet (e.g. Moran *et al*., in press).

Staenz and Itten (1982) investigated the suitability of asphalt and concrete surfaces for use as ground calibration targets. They concluded that both were suitable, however, they noted that some types of concrete had a grooved surface which introduced an undesirable bidirectional effect. Lawless *et al*. (1998) made repeated reflectance measurements of two concrete and asphalt surfaces over a period of several weeks and found no statistically significant changes in the reflectance of the asphalt surface in either the visible or near infra-red region, and no statistically significant changes in the reflectance of the concrete surface in the visible region. However, they did find a small, though significant, change in the near infra-red reflectance of the concrete surface. This result has since been replicated by measurements on another disused Second World War airfield in southern England. Figure 4 shows the variability around the mean reflectance in red and near infra-red bands for four ground calibration targets which were measured four times during May 1999. The greatest variability was observed for the concrete surface.

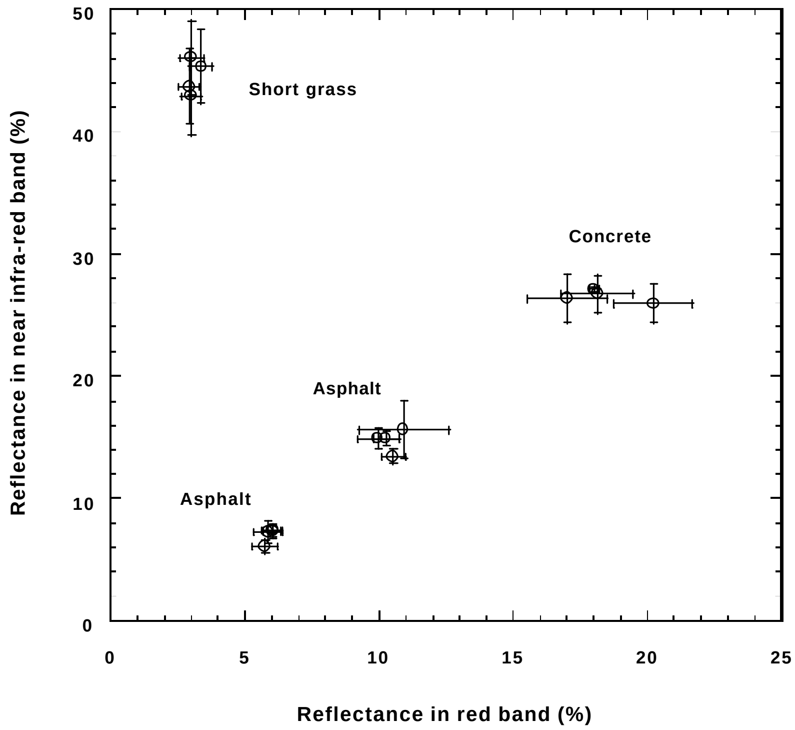


Figure 4: Variability around the mean reflectance (±1 s.d.) over a period of one month for four potential ground calibration sites: concrete, asphalt (two types) and short grass.

3.3 An example of the use of ground calibration targets

Imaging spectrometers such as *casi* are well-suited to studying phenological changes in vegetation canopies since they provide fine spectral resolution and many spectral bands, allowing subtle phenological changes to be observed. However, for this to be achieved, it is essential that the data are calibrated to reflectance so that those spectral changes in the canopy due to variations in pigment concentration and biophysical processes can be distinguished from those caused by variations in the atmosphere or the conditions of illumination and viewing.

In 1995 a study was undertaken using the NERC *casi* to investigate seasonal changes in the reflectance of heather canopies, in order to test the hypothesis that the profuse flowering characteristic of such canopies would reduce the effectiveness of the NDVI and other commonly-used vegetation indices (Milton and Rollin, 1990). More details of this study can be found in Emery *et al*. (1998).

Figure 5 shows average reflectance spectra measured in the field from a *Calluna vulgaris* canopy at three critical times during the growing season: in mid-summer at the time of maximum green leaf development, in late-summer at the time of maximum flower development and in autumn at the time of winter browning. These spectra were used to produce a bandset optimised for the for monitoring of seasonal changes in heathland canopies (Table 1).

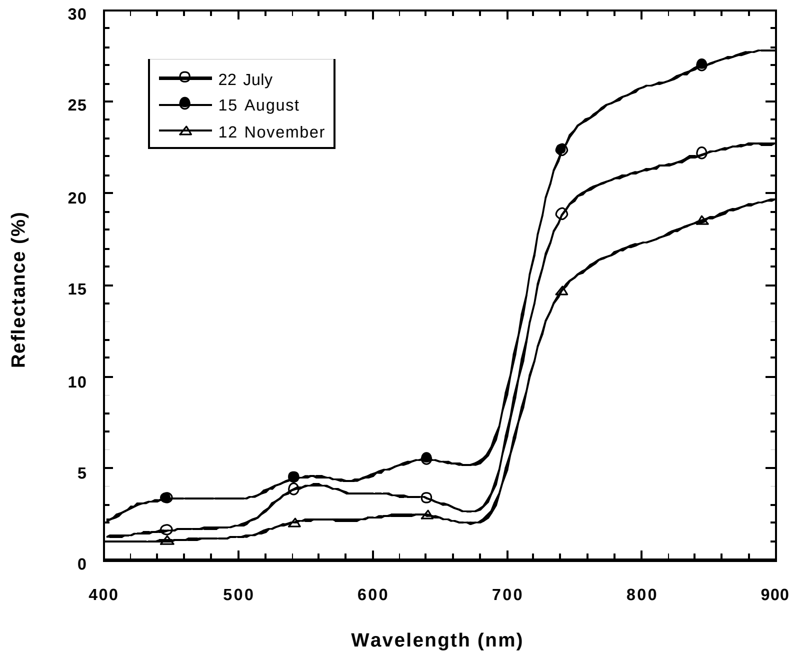


Figure 5

Temporal changes in heathland reflectance measured in the field.
Max. greenness (July), max. flowering (August), canopy browning (November).

casi data were collected by NERC at three important times in the heathland seasonal cycle during the 1995 growing season. Data were collected from an altitude of 4400 feet using NERC's default vegetation bandset during the green-up period on 28 June and using both the default vegetation bandset and the heathland bandset on 17 August, during peak flowering, and 2 November, when the heath was browning.

Table 1: *casi* spatial mode heathland bandset as optimised for monitoring seasonal changes in *Calluna* canopies, compared with the NERC 'Default Vegetation' bandset.

Band	Default bandset (nm)		Heathland bandset (nm)	
	Centre	Bandwidth	Centre	Bandwidth
1	450	20	450	20
2	552	10	552	10
3	670	10	580	10
4	700	10	600	10
5	710	10	635	10
6	740	10	670	10
7	750	7	710	10
8	780	10	750	10
9	820	10	780	10
10	865	10	820	10

Five ground calibration targets were identified in the area prior to the flights and their spectral reflectance measured during the flights using spectroradiometers borrowed from the NERC EPFS (Figure 6). Four bare surfaces were measured: two types of asphalt, an area of concrete and a uniform area of heavily grazed lawn. The two asphalt surfaces, the gravel and the grass lawn were used to derive the calibration.

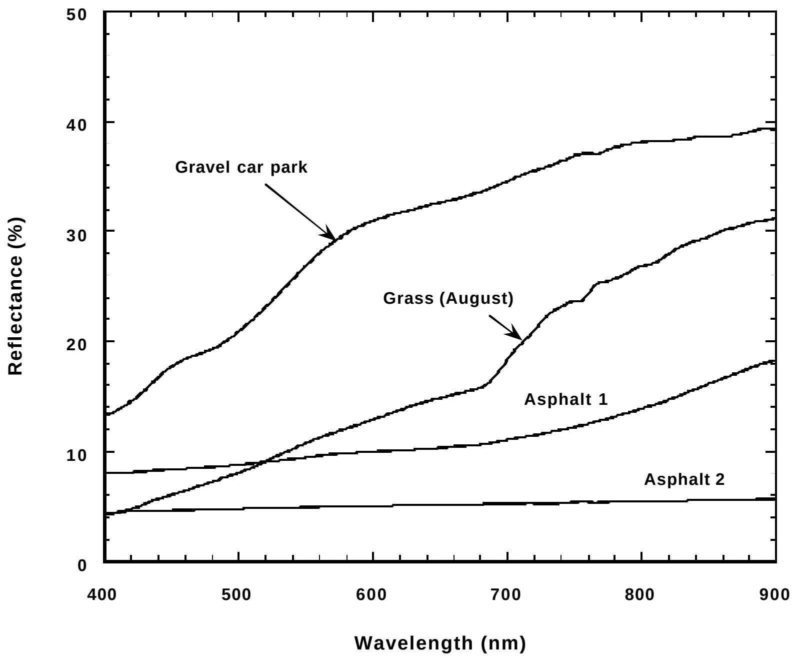
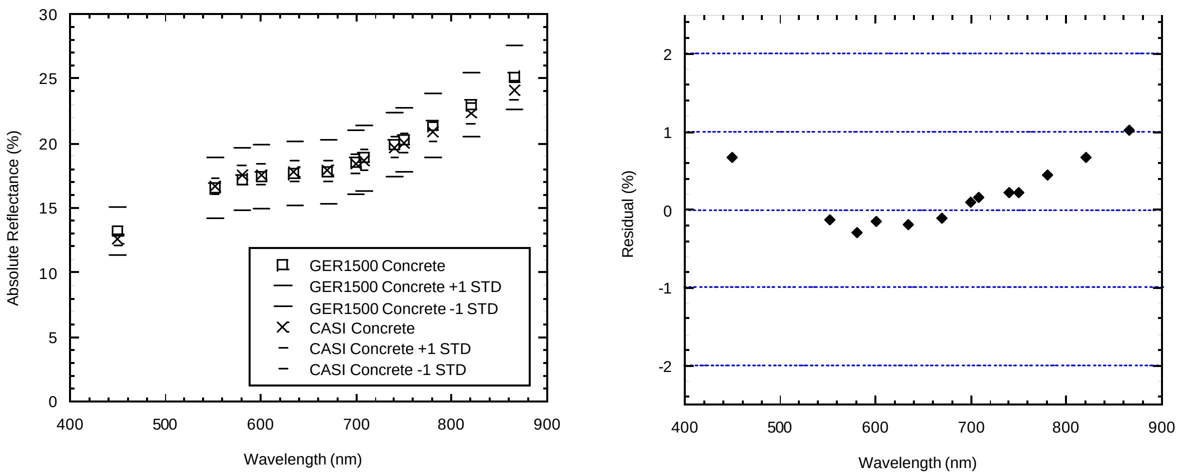


Figure 6: Ground calibration target spectra measured in the field.

The resulting calibrated image was tested by comparing the *casi* reflectance spectrum for the area of concrete not used in the calibration with that measured on the ground (Figure 7). The *casi* spectrum was within 1% of the ‘true’ value at all wavelengths.

Figure 7: Test of the reflectance calibration.



(a) comparison of the *casi* reflectance of an area of concrete with that measured at ground level; (b) percentage difference between the two

It is beyond the scope of this paper to discuss the application of these results, but an indication of the information present in the reflectance calibrated images may be gained from Figure 8 which shows the seasonal change in spectral reflectance of a stand of *Calluna* measured by *casi*. This figure shows how, in late-summer, the characteristic green vegetation spectrum has been modified by the presence of flowers so as to mask completely the usual absorption in red wavelengths due to plant pigments. Furthmore, this figure shows major seasonal variation in the location of the red edge. If the location of the red-edge were to be calculated from uncalibrated data it would probably be in error. Only by calibrating the data to reflectance can the accurate location of the red-edge be determined.

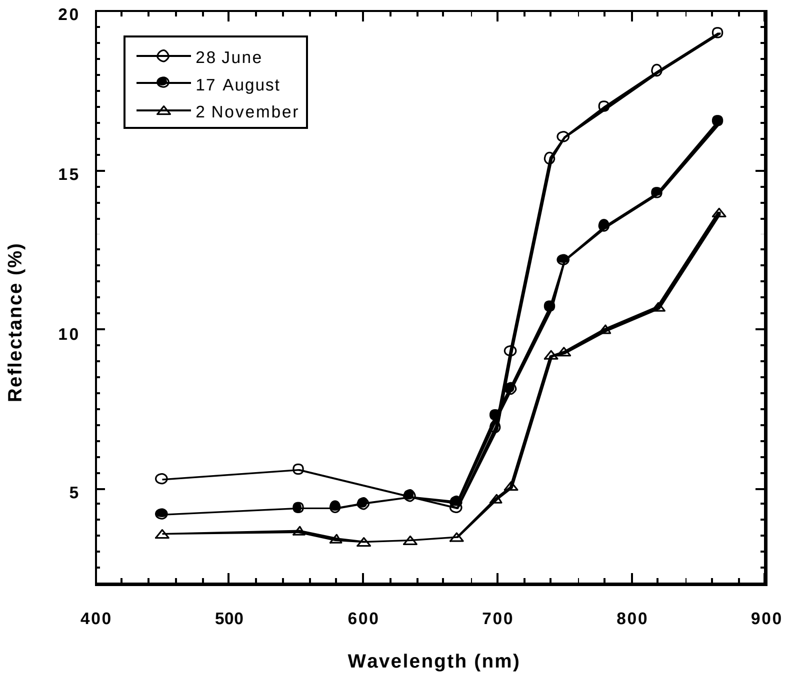


Figure 8: *casi* reflectance spectra of heathland dominated by *Calluna vulgaris* at times of maximum greenness (late June), maximum flower development (mid-August), and the onset of winter browning (November)

In contrast, Figure 9 shows the seasonal trend in reflectance of an area of short grass determined from the same calibrated *casi* data sets. In this case, the absorption feature in red wavelengths is present at all dates, although it is slightly weaker in mid-August. The maximum slope of the red-edge shows very slight variability between the three dates, but the major change is to the upper lip of the red-edge, which is lower and more rounded in August than either late-June or November.

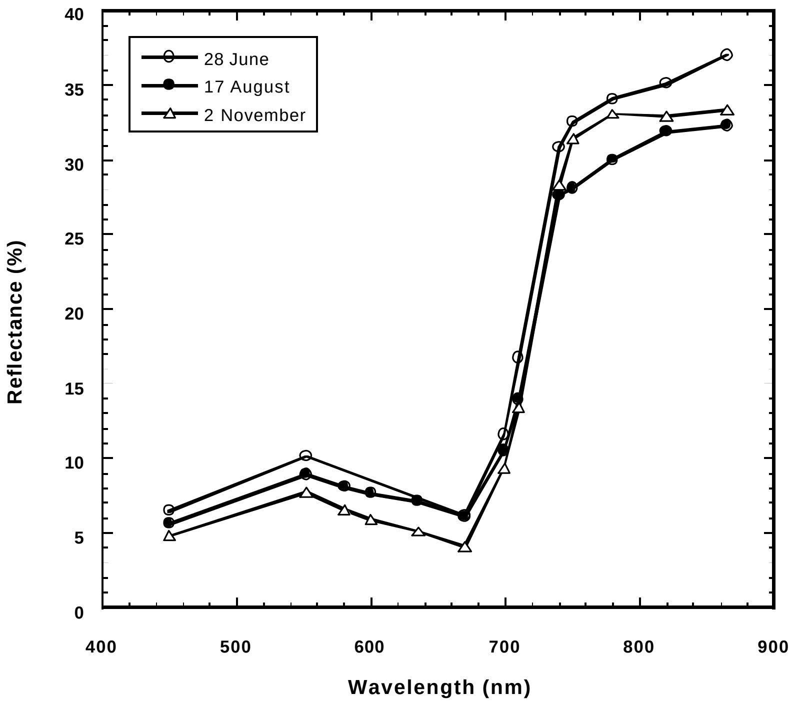


Figure 9: Seasonal trend in reflectance from an area of short grass determined from the reflectance calibrated *casi* data

4. Conclusion

Reflectance calibration of *casi* data is not a trivial task. Even though the methods presented here are simple to implement, they require considerable planning and attention to detail if they are to deliver good results. Improvements in the *casi* sensor, and in particular, in the ILS and its mounting in the airframe, are necessary before ILS data can be recommended for use in atmospheric correction. Well-characterised ground targets are very useful in any *casi* survey as they can be used to generate an atmospheric correction, or they can be used to verify an alternative method. The best results are likely to be obtained by combining more than one technique, or by using multiple techniques in parallel so as to converge upon an accurate atmospheric correction. However, it is important to bear in mind that methods which may work well in a continental desert or semi-arid area may fail completely when applied to a study area dominated by moist, maritime air masses. Continued research on this topic in the UK is essential if quantitative airborne remote sensing is to progress in the European context.

5. Acknowledgements

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