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INSTITUTE OF TERRESTRIAL ECOLOGY
(NATURAL ENVIRONMENT RESEARCH COUNCIL)

Project T13061D7

INCIDENT LIGHT SENSOR (ILS) INTERCALIBRATION

FINAL REPORT

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CONTENTS

SUMMARY

This report has been prepared to present the results and findings of a short consultancy service undertaken by the Natural Environment Research Council (NERC) Institute of Terrestrial Ecology (ITE) for the NERC Scientific Services (NSS). This work followed on from the **Consultancy Service NS/95/CON/4** that ran from November 1995 to January 1996. The work described here is related to the development of intercalibration procedures for the Incident Light Sensor (ILS) on the Compact Airborne Spectrographic Imager (*casi*) of the NERC Airborne Remote Sensing Facility (ARSF). The above task used airborne and ground data acquired in November 1995 at Goodwood Aerodrome near Chichester. Two methods for ILS intercalibration were tested. Intercalibration against an instrument with a traceable calibration was found to be the most accurate due to the rigid configuration of the NERC *casi* and ILS when attempting to intercalibrate against a reference panel. An examination of the Goodwood intercalibration experiment identified issues that should be considered when planning future intercalibrations. The results of the intercalibrations identified issues concerning the characterisation, operation and processing of the ILS that must be investigated before the ILS intercalibration can be truly operational.

1. INTRODUCTION.

NERC Scientific Services (NSS) operate a group of Responsive Mode Services that includes the Airborne Remote Sensing Facility (ARSF) (Wilson, 1995), whose aim is to collect remotely sensed data in support of the UK research community. ARSF began collecting data in 1982 using hired equipment, but since then it has gradually purchased its own aircraft and instruments and undertaken up-grading of the instruments.

One of the instruments flown by the ARSF is an Itres Research Compact Airborne Spectrographic Imager (***casi***), a pushbroom imaging spectrograph that uses a two dimensional charge couple device (CCD) to record the spatial and spectral data for a whole image line simultaneously. It records images 512 pixels wide in up to 15 selectable spectral wavebands of varying band width or complete spectra in the range 400 nm to 915 nm with a spectral resolution of 1.8 nm for 39 separate look directions. Recent developments have produced a third option, enhanced spectral mode, where complete spectra can be collected for a centrally located block of 101 look directions.

The ***casi*** is equipped with an incident light sensor (ILS) which records the down-welling irradiance at the aircraft. The ILS cosine receptor, which consists of a flat disc of Teflon, is located on the fuselage above the cockpit and is connected to the ***casi*** optical head by a fibre optic cable. The data from the ILS is recorded as either pixel 512 or look direction 40 by the Itres Research software, depending on whether the ***casi*** is operating in spatial or spectral mode respectively. The ILS shares optics, detectors and electronics with the imaging portion of the ***casi***. The ILS has a low signal-to-noise ratio (SNR), but has been found to detect changes in the down-welling irradiance rather than noise (Shepherd and Xu, 1993). During the laboratory calibration of the ***casi*** the ILS is not connected and no calibration coefficients are calculated for it. After calibration of ***casi*** image data to radiance the ILS data remains as raw data numbers with only the system offsets, such as dark current, being removed (Itres Research, 1995).

2. METHODS FOR CALIBRATING THE ILS

The simplest method for calibrating the ***casi*** ILS is to measure the down-welling irradiance concurrently with both the ILS and another instrument whose calibration is traceable to a known source. Assuming that system offsets have been removed from the ILS data then a calibration coefficient (c) can be calculated using

$$c_i = E_i / DNils_i \qquad 1.$$

where $DNils$ is the raw data numbers (DN) recorded by the ILS, E is the irradiance recorded by the traceable instrument and i is the waveband. The set of calibration coefficients can be used to convert ILS DNs to units of irradiance.

A number of researchers have calibrated the ILS without the use of a separate traceable instrument (Xu *et al.*, 1993, Shepherd and Xu, 1993 and Williams *et al.*, 1992). The preferred procedure is to place a reference panel in the field-of-view (FOV) of the ***casi*** optical head and position the ILS cosine receptor next to the reference panel. Image data for the reference panel and ILS data are collected concurrently with the ***casi*** and the image data are processed to units of radiance. A correction coefficient (k) can be calculated as follows;

$$k_i = \rho p_i * (L_i / DNils_i) \qquad 2.$$

where ρp is the reflectance of the reference panel and L is the radiance of the reference panel from the image. This procedure is analogous to the head intercalibration performed with the Spectron (Appendix A). k allows down-welling irradiance to be estimated from the data numbers recorded by the ILS as follows

$$E_i = k_i * DNils_i * \pi \qquad 3.$$

and the ratio of image to ILS data can be converted to reflectance by

$$\rho s_i = k_i * (DNils_i / L_i) \qquad 4.$$

where ρs_i is the estimate of surface reflectance.

3. INTERCALIBRATION EXPERIMENT AT GOODWOOD

An experiment was performed at Goodwood Aerodrome to apply the methods to the intercalibration of the ILS described above. A Spectron spectroradiometer (Appendix A), which has a cosine head for the direct measurement of down-welling irradiance, was used as the instrument with a traceable calibration. The method for the intercalibration against a reference panel could not be followed exactly as described because the NERC ILS cosine-receptor is permanently attached to the aircraft and could not be placed next to the reference panel below the aircraft easily. It was therefore necessary to assume that the light environments of the cockpit roof and the ground beneath the tail of the aircraft were reasonably similar.

On the 6th November 1995, the NERC aircraft landed at Goodwood Aerodrome 3 km north-east of the centre of Chichester (Figure 3.1) to facilitate the collection of measurements for the intercalibration of the ILS. The aircraft was parked between two hangars on a small area of concrete apron with the tail section, which contained the ***casi*** optical head, overhanging a grassed area (Figure 3.2). It was necessary to park the aircraft near a hangar so that ground power could be obtained to operate the instruments while the engines were not running.

The Spectron was set up to record data in cos-conical mode (Appendix A), but only for the measurement of down-welling irradiance and up-welling radiance rather than the calculation of reflectance. The Spectron cosine head (S/N 1214) was set up and levelled on a tripod that was placed on the aircraft wing along side the fuselage to be

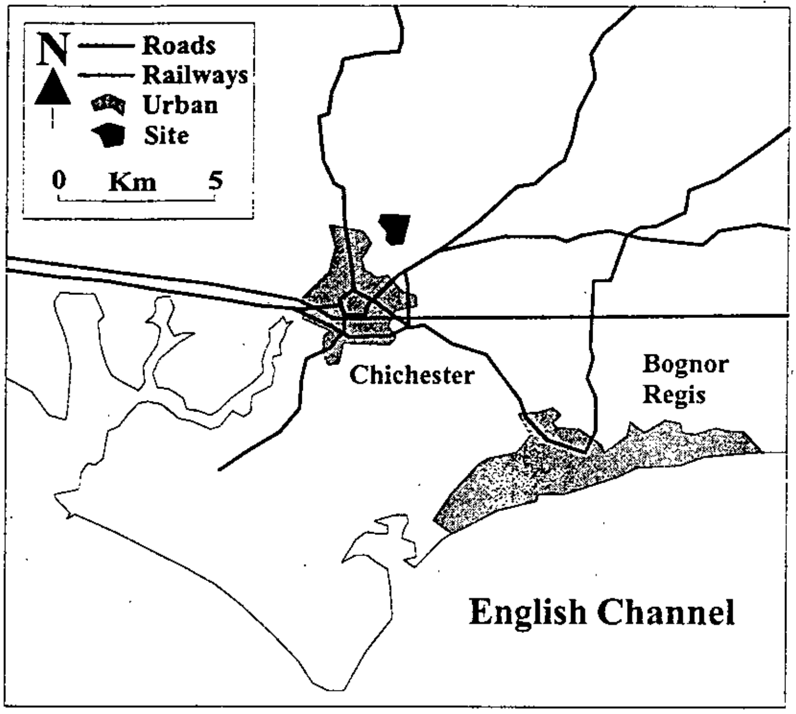

Figure 3.1: The location of Goodwood Aerodrome.

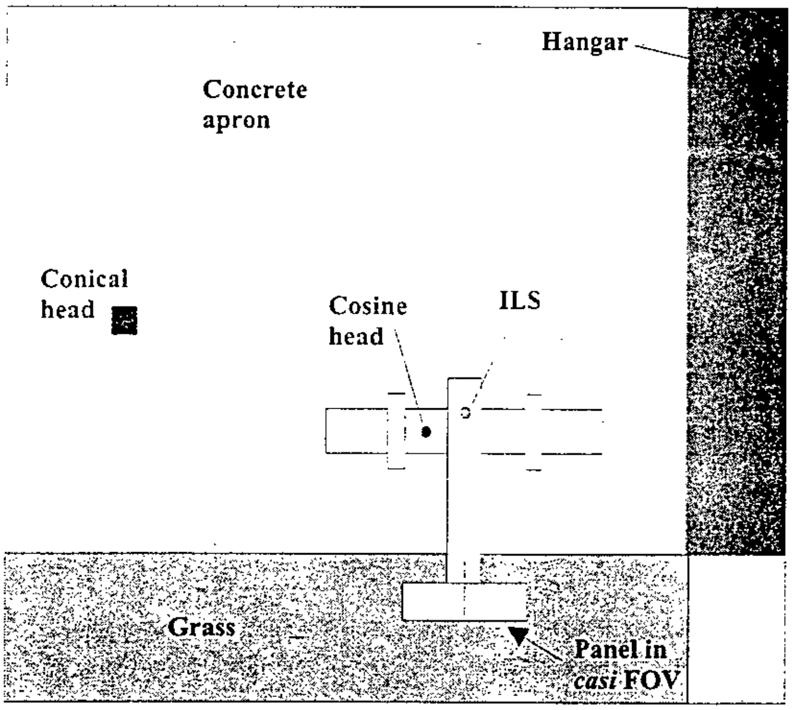

Figure 3.2: The location of the NERC aircraft and intercalibration instruments relative to buildings and surfaces at Goodwood Aerodrome during the ILS intercalibration experiment.

as close to the ILS cosine receptor as possible. The proximity of the eastern hangar was of some concern as both irradiance detectors had to be in the same light environment. The Spectron conical head (S/N 1447) was used to collect measurements of radiance from a Spectralon^{TM} 99% reference panel (SRT2707) placed in the open on the concrete apron. A second Spectralon^{TM} 99% reference panel (SRT1011) was placed on the grass beneath the tail section of the aircraft within the FOV of the ***casi***.

The measurement sequence consisted of concurrent measurements with the Spectron and ***casi***. The Spectron alternately collected measurements from the cosine and conical heads while the ***casi*** collected images of the reference panel and ILS data in spectral mode. Data were collected between 13:45 and 13:51 GMT. In early November the Sun was quite low in the sky with an elevation of approximately 18° and directly behind the aircraft. The sky was slightly hazy with some small amounts of cumulus near the horizon. A total of fifteen irradiance and fifteen radiance spectra were collected with the Spectron. The ***casi*** collected in excess of 2000 lines of data.

3.1 PROCESSING OF THE DATA COLLECTED AT GOODWOOD

The Spectron data were processed at the Geography Department, University of Southampton in November 1995 while the ***casi*** data were processed through the Integrated Data System (IDS) at the NERC ITE Monks Wood in October 1996.

3.1.1 Spectron data

The Spectron data were downloaded from tape and three of the spectra were found to be unrecoverable.

The measurements from the Spectron cosine head were calibrated to irradiance in units of $mWm^{-2}nm^{-1}$ using the most recent calibration file, `e941214n.cos`, for that cosine head (Appendix A). The Spectron irradiance spectra were found to be very similar, with the only differences being consistent with a decrease in solar elevation during the data collection. A mean irradiance spectrum was calculated in units of $\mu Wcm^{-2}nm^{-1}$ (Figure 3.3). The coefficient of variation spectrum (Figure 3.4) shows that the variation in irradiance was less than 2% of the mean value over the wavelength range under investigation.

The measurements from the Spectron conical head were calibrated to radiance in units of $mWm^{-2}sr^{-1}nm^{-1}$ using the most recent calibration file, `1941447.15`, for that conical head (Appendix A). The Spectron radiance spectra were more variable than the irradiance spectra and the changes were not related to a decrease in solar elevation. The reference panel (SRT2707) measured by the conical head was smaller than the usual reference panels and the 15° FOV conical head was hand held on a long handle above the panel. This situation resulted in some alignment problems and therefore changes in the measured radiance. The Spectron radiance data were therefore only used to check the calibration of the imagery of the reference panel (SRT1011) viewed by the ***casi*** and not used directly in the intercalibration of the ILS.

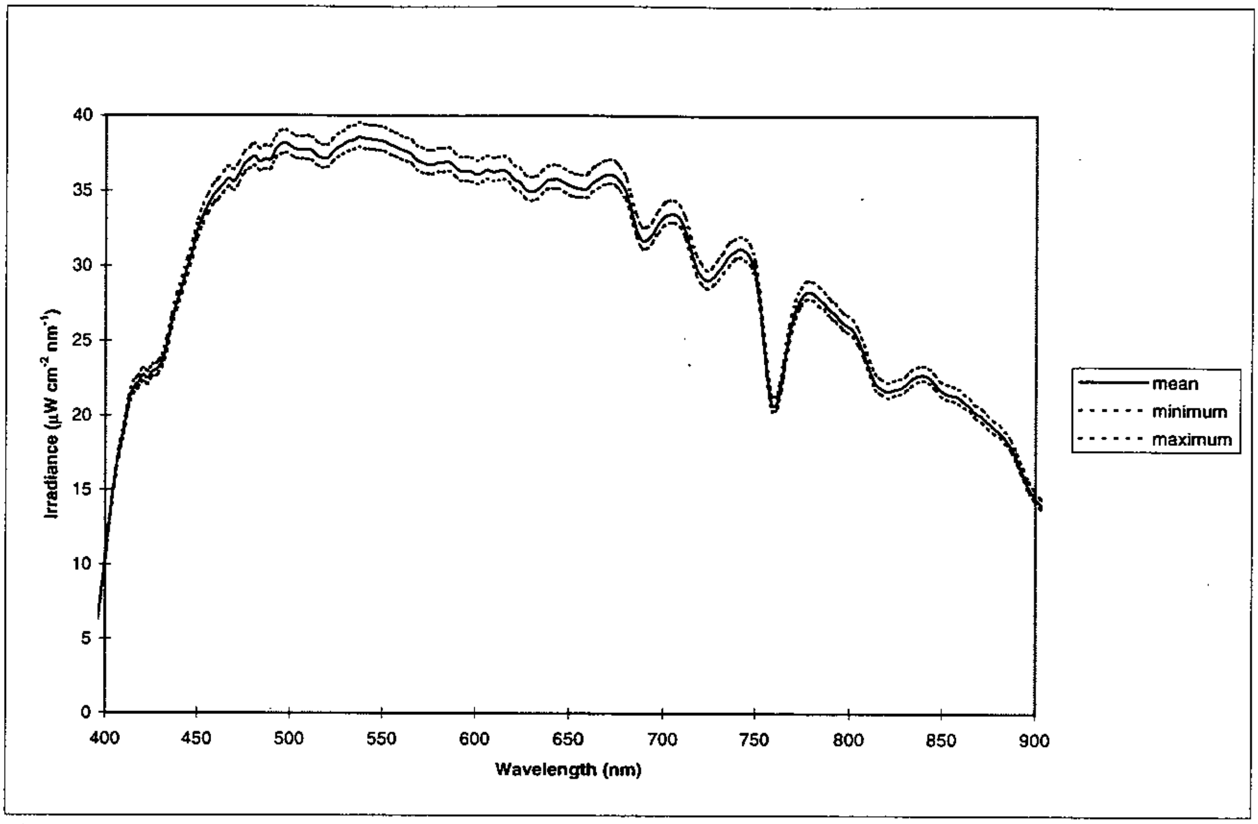

Figure 3.3: The mean, minimum and maximum irradiance spectra recorded with the Spectron cosine head.

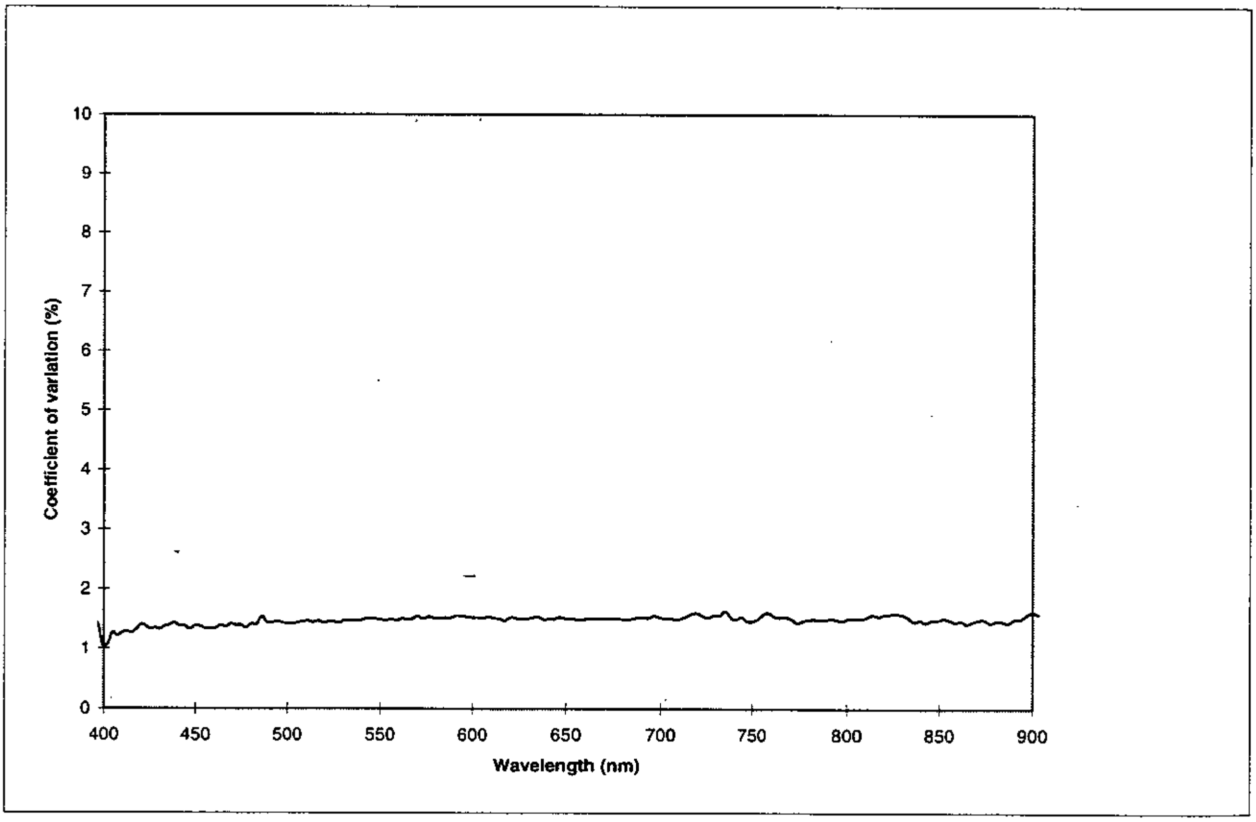

Figure 3.4: The coefficient of variation spectrum of the irradiance recorded with the Spectron cosine head.

3.1.2 *casi* data

The ***casi*** ILS data were processed through the IDS to raw data numbers with only the system offsets, such as dark current, being removed. The ***casi*** image data were processed to level 1b that includes a full radiometric calibration, in this case relative to the NERCCAL6 ***casi*** calibration undertaken at the NERC EPFS in April 1995. These data were supplied as separate generic binary files in band interleaved by line (BIL) format. The ILS data were then processed to produce statistics (mean, standard deviation, coefficient of variance, minimum and maximum) in each waveband. After the selection of the image area relating to the reference panel, the image data were also processed to produce the same statistics.

The maximum ILS DN (Figure 3.5) was less than 120 which is small compared to the image that ranged from 250 to 2500. The range of ILS DNs in each band was large with a coefficient of variation (Figure 3.6) in each band of up to 50% of the mean value below 450 nm and greater than 10% for more than half of the wavelength range under consideration. From a knowledge of the irradiance spectrum recorded at the same time the shape of the ILS spectrum suggested that the transmittance band of the ILS (Teflon cosine receptor, fibre optic cable, etc.) was much narrower spectrally than the wavelength range of the ***casi***.

The signal-to-noise ratio (SNR) of the ILS was calculated from the mean and standard deviation of the DNs in each waveband (Smith and Curran, 1996). The ILS is known to have a poor SNR, but for over half of the wavelength range the NERC ILS (Figure 3.7) had a SNR of less than 10:1. Taking the variation in irradiance during the data acquisition into account would not significantly improve the SNR results. It appears that the ILS has a usable wavelength range of 500 nm to 650 nm at best.

A comparison of the NERC ILS data to ILS data from a ***casi*** flown by Nakanihon Air Services (NAS) (Anger *et al.*, 1994) (Figure 3.8) shows large differences in the dynamic range of the DNs and the shape of the spectrum, even though they were assumed to have been processed to the same level. The NAS ILS data had DNs 15 times larger than those recorded by the NERC instrument. The ILS spectra had similar shapes between 400 nm and their peak response around 600 nm. The DNs of the NERC ILS fell off dramatically between 600 nm and 700 nm to give a relatively flat spectrum out to 900 nm. The NAS ILS spectrum had a steady decrease in DN between 600 nm and 900 nm.

The ILS data is highly variable relative to the irradiance spectra recorded by the Spectron. Fortunately, the large number of ILS spectra recorded by the ***casi*** (2134 compared to 13 by the Spectron) allowed the mean value to be used as an estimate of the actual ILS data during acquisition.

The mean radiance spectrum of the reference panel from the ***casi*** image data was compared to the radiance of the reference panel recorded by the Spectron. The Spectron data were multiplied by a ratio of the panel reflectances and resampled spectrally (Appendix B.) to the wavebands of the ***casi*** (Figure 3.9). The ***casi*** and Spectron radiance spectra are very similar over most of the wavelength range under investigation, bearing mind the different spectral resolutions employed by each

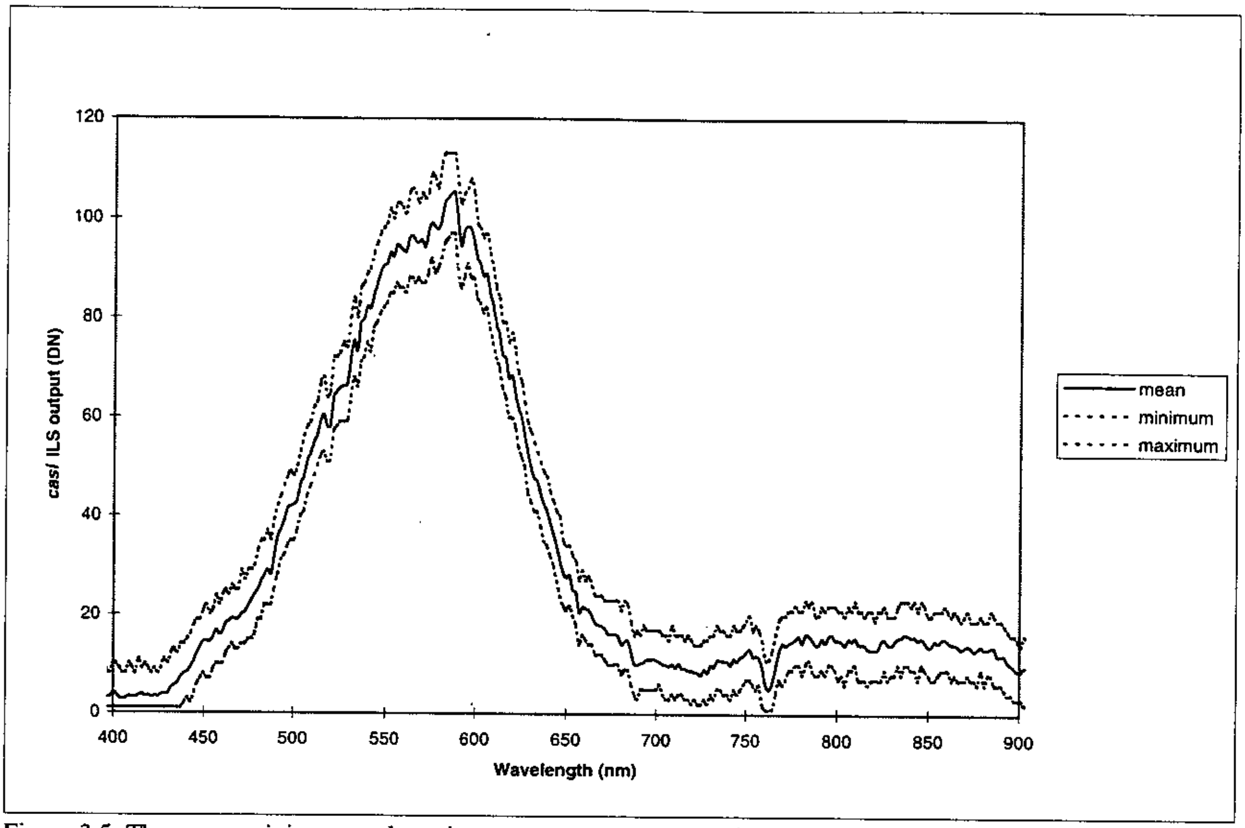

Figure 3.5: The mean, minimum and maximum output spectra recorded by the ILS.

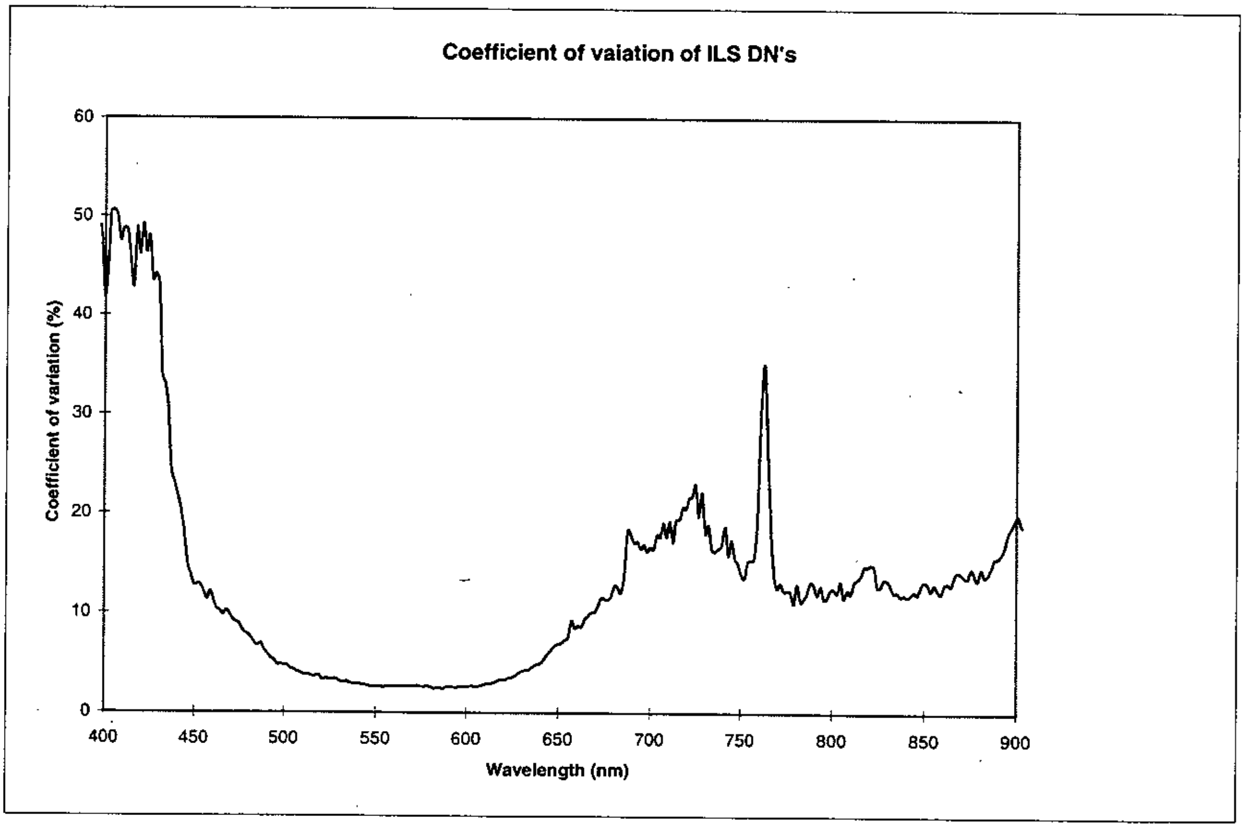

Figure 3.6: The coefficient of variation spectrum of the output spectra recorded by the ILS.

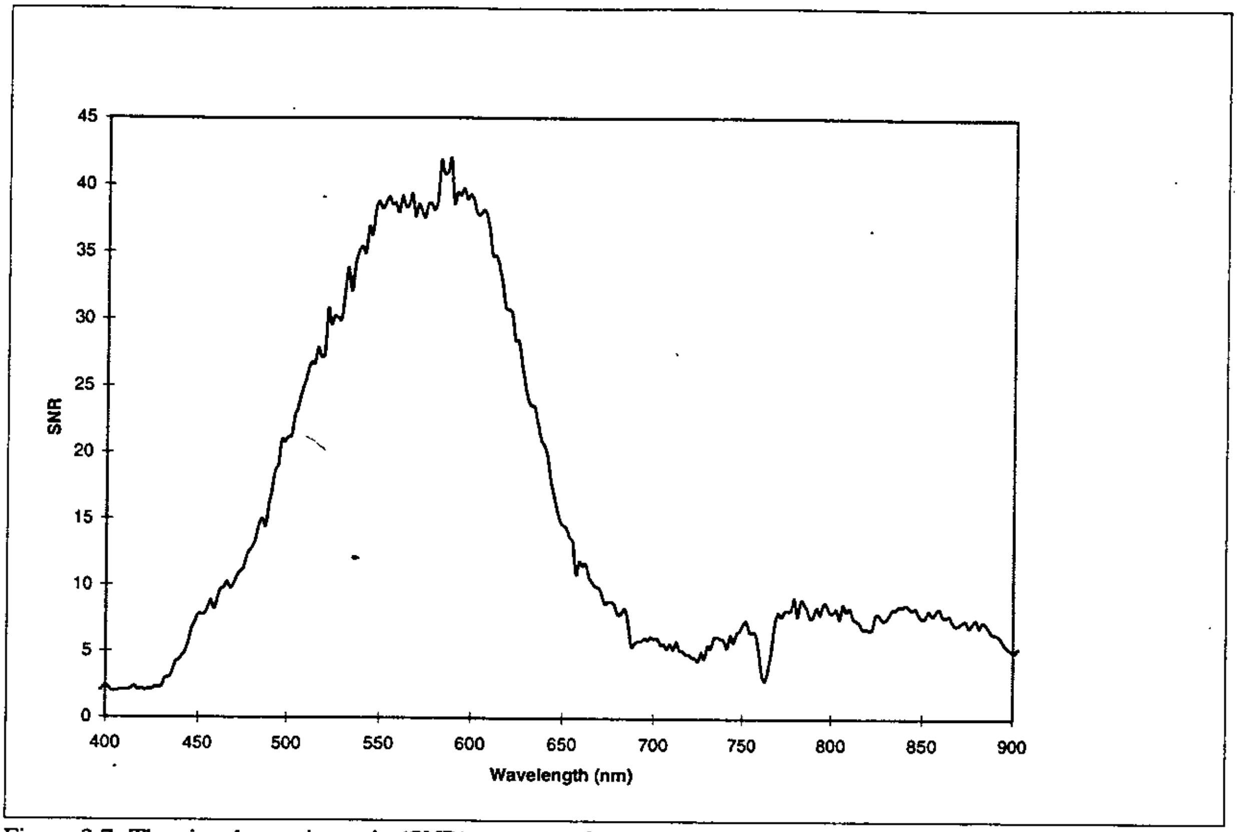

Figure 3.7: The signal-to-noise ratio (SNR) spectrum for the ILS.

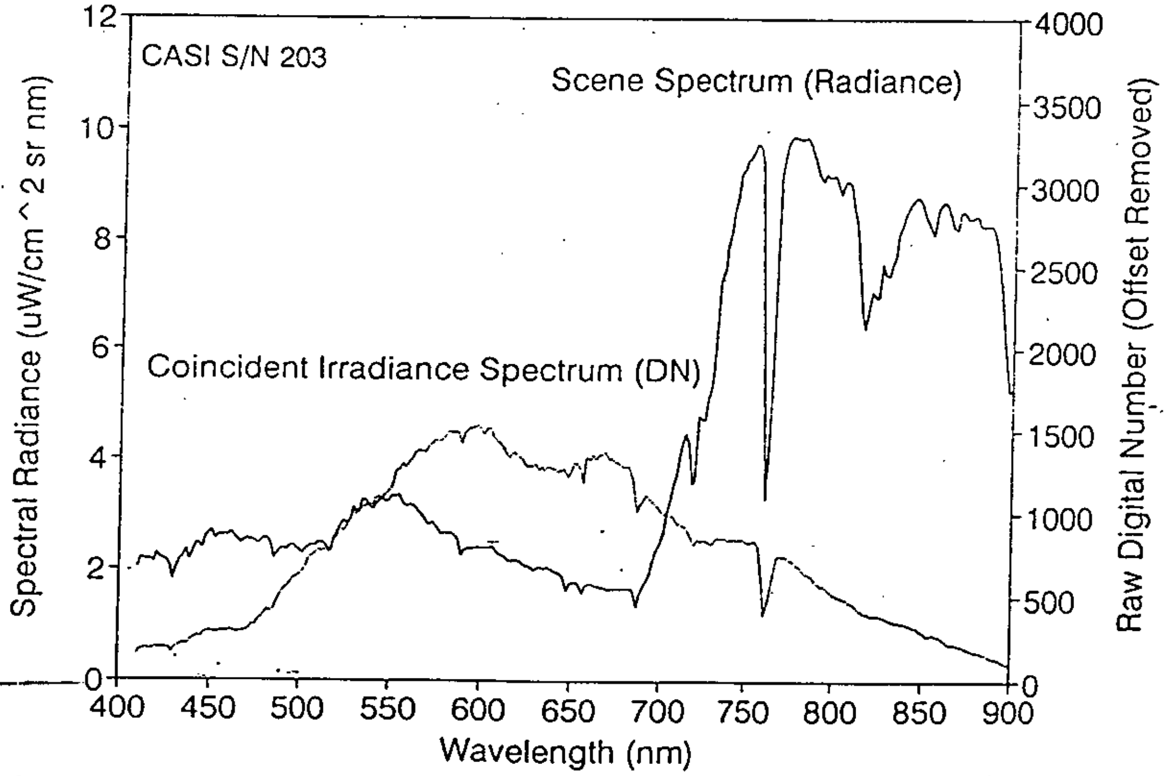

Figure 3.8: Spectral mode data from a *casi* flown by Nakanihon Air Services, Japan (Anger et al.,1994).

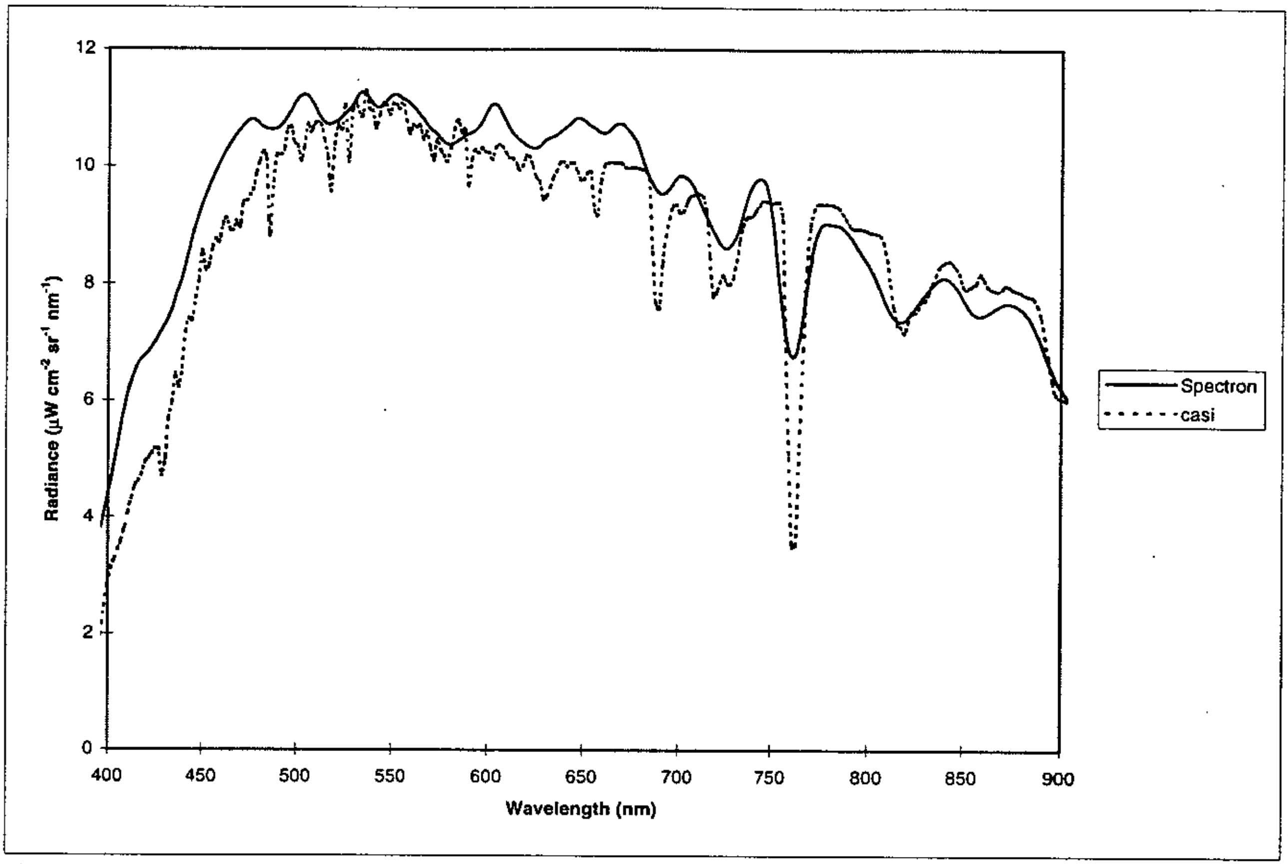

Figure 3.9: A comparison of the radiances recorded by the casi for for the reference panel SRT1011 and the Spectron for the reference panel SRT2707.

instrument. They do deviate below 500 nm, although it is unclear how much of this deviation is due to the light environments around the two reference panels.

3.2 INTERCALIBRATION AGAINST AN INSTRUMENT WITH TRACEABLE CALIBRATION

The mean irradiance spectrum recorded by the Spectron was resampled spectrally to the wavebands of the ***casi***. A set of calibration coefficients (Appendix C.) was calculated from the mean irradiance spectrum and the mean ILS DN spectrum using equation 1. This produced a spectrum of calibration coefficients (Figure 3.10) which could be applied to the ILS DNs to produce an irradiance spectrum.

3.3 INTERCALIBRATION AGAINST A REFERENCE PANEL DATA

The reflectance of the reference panel was resampled spectrally to the wavebands of the ***casi***. A set of correction coefficients (Appendix D.) was calculated using the reflectance of the reference panel, the mean radiance of the panel from the image data and the mean ILS DN using equation 2. This produced a set of correction factors (Figure 3.11) which were applied to the ILS DNs in equation 3 to estimate the irradiance recorded by the ILS (Figure 3.12). The ILS estimated irradiance is generally less than the Spectron irradiance suggesting there are differences in the light environments between the top of the cockpit and the ground beneath the tail section of the aircraft.

4. LIMITATION OF GOODWOOD INTERCALIBRATION EXPERIMENT

Before discussing the results of the ILS intercalibration experiment at Goodwood a number of limitations that became obvious during the data collection should be highlighted and borne in mind before performing future intercalibrations. The ILS is known to have a low SNR and combined with the low sun angle in November would have reduced the radiation incident on the cosine receptor and therefore the level of the signal recorded. The timing of the ILS intercalibration should be set to maximise the amount of down-welling radiation. The light environment around the aircraft was controlled by the need for ground power to operate the instruments. Provision should be made to have the aircraft as far from buildings as possible to minimise the amount of radiation scattered from them towards the instruments. A certain amount of multiple reflection would occur beneath the tail section of the aircraft, between the highly reflective paint work of the aircraft and the surface. The surface around the reference panel was grass at Goodwood, but some form of spectrally black out cloth would have been more appropriate.

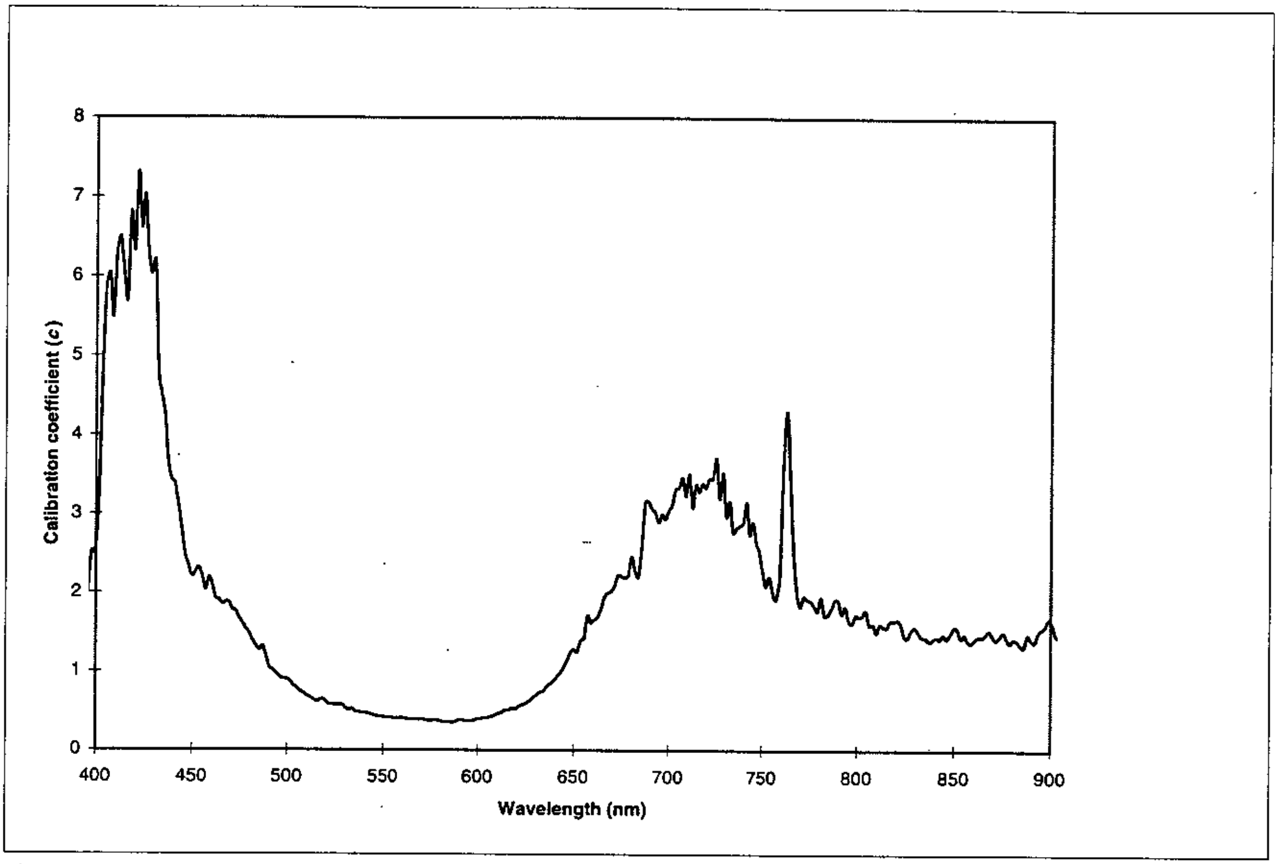

Figure 3.10: Calibration coefficient (c) for the ILS intercalibration against an instrument with a traceable calibration.

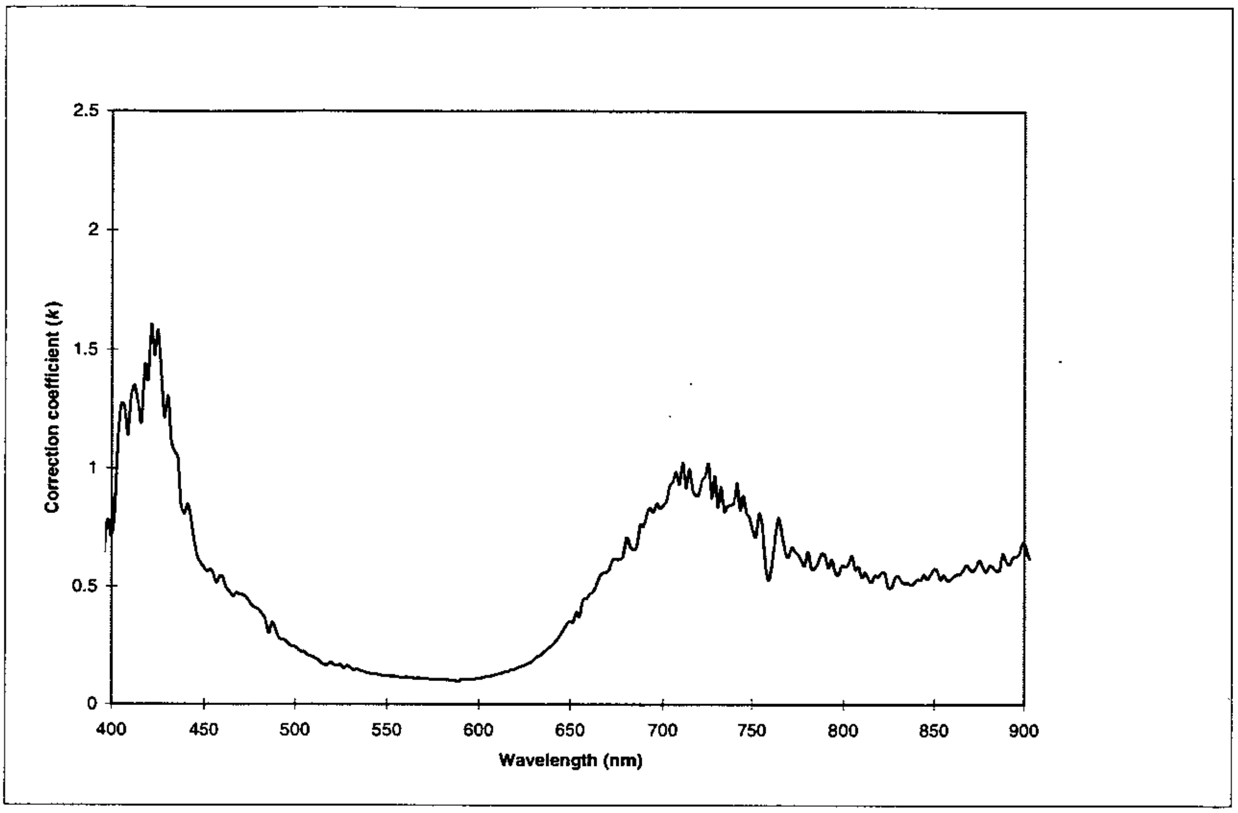

Figure 3.11: Correction coefficient (k) for the ILS intercalibration against a reference panel.

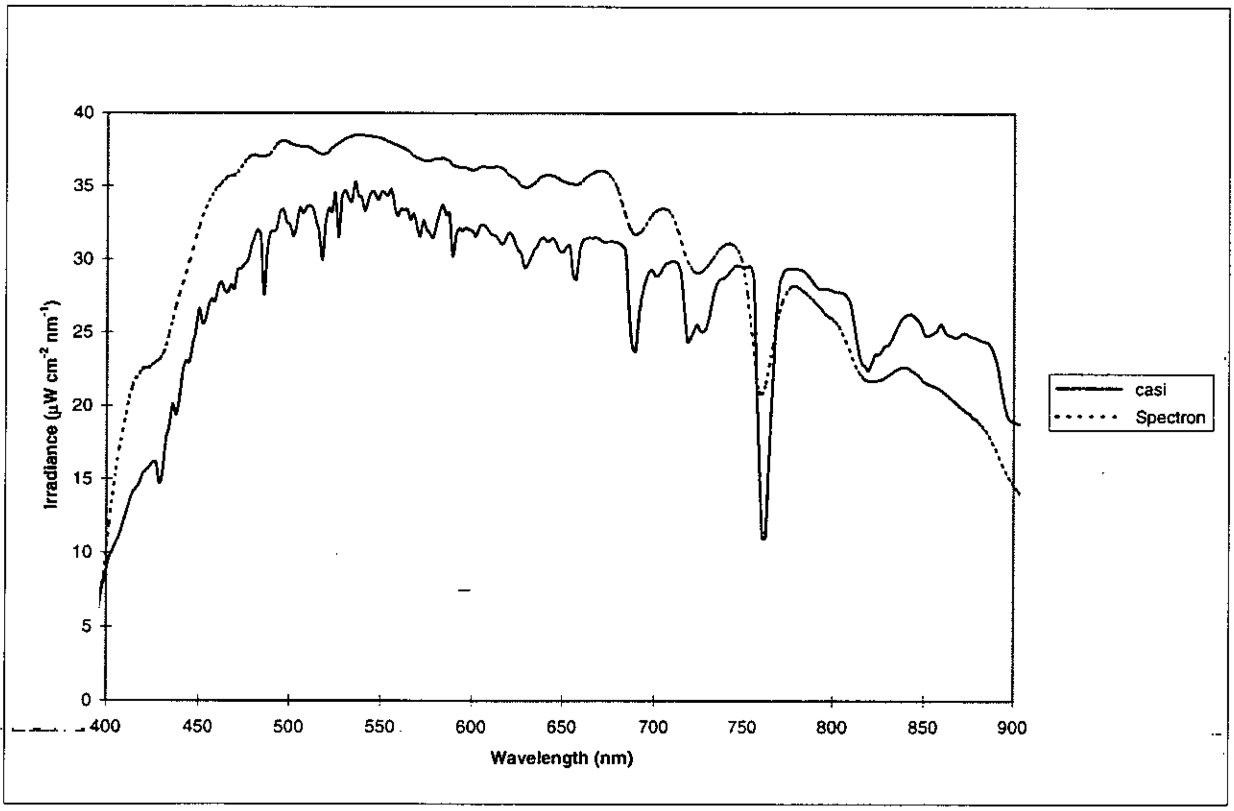

Figure 3.12: A comparison of the irradiances recorded by the Spectron and estimated by the ILS after intercalibration against a reference panel.

5. DISCUSSION

This intercalibration used ***casi*** data in spectral mode only, as software is available to convert any results generated in spectral mode to any given spatial mode without resorting to additional field measurements.

From the results of the two methods for the intercalibration of the ILS, it can be seen that they are both suitable for an operational procedure, but they have certain limitations. Intercalibration against an instrument with a traceable calibration is the most accurate approach. but this requires additional equipment and field measurements. Intercalibration against a reference panel is logistically simple, only requiring the panel to placed in the ***casi*** FOV, but the inability to put the ILS and the panel next to each other (different light environments of the cockpit roof and tarmac beneath the aircraft) reduces the accuracy of the ILS calibration.

The issues that were raised in section 4 should be considered when using either of the methods to maximise the accuracy and repeatability of the intercalibration procedure. These issues have been incorporated into the ILS intercalibration procedure outlined in section 7.

Before this procedure can be truly operational a much fuller understanding of the character, operation and processing of the ILS must be obtained. Section 3.1.2 highlighted the unusual spectral response of the ILS compared to what other ***casi*** users have found and what would be expected of a sensor designed to measure irradiance in the 400 nm to 900 nm wavelength range. The spectral response of the ILS must be characterised by relating the output from the ILS (Teflon cosine receptor, fibre optic cable, etc.) to known inputs. Improvements should be investigated which increase the transmittance of the ILS and therefore it's recorded signal. The operation of the ILS was thought to be very similar to the image part of the ***casi***, but this is now unclear. It has been suggested that when the dark current measurements are made at the beginning of data collection, to allow the removal of system offsets from the recorded DNs, the ILS detectors are not in fact shuttered. The removal of system offsets from the ILS data is then meaningless as the value that is being removed is that recorded by an illuminated detector. This could explain the small DNs (sometimes zero) recorded by the ILS after the removal of system offsets. Itres Research appear to be unsure of exactly what happens to the ILS data when it is processed by *radcorr*. Processing routines to properly remove the system offsets from ILS data have apparently been developed at Itres Research, but they are not available currently. The absence of the ILS from the laboratory calibration procedure requires the extraction of the ILS data at an intermediate point within the full ***casi*** calibration procedure. It is unclear if the correction of DNs for integration time has been done at this point. If not, then the DNs being used for the ILS are not in the correct units of watts (Js^{-1}). This could also explain the small DNs of the ILS as multipliers in the range 5 to 50 would be used in this correction depending on the integration time. These issues must be addressed and answered before ILS data can be calibrated on an operational basis.

Once calibrated, ILS data collected inflight must also be corrected for aircraft attitude as changes in roll, pitch and yaw will change the hemisphere over which irradiance is being sampled.

6. CONCLUSIONS

This work has tested two methods for ILS intercalibration and generated two sets of coefficients for converting ILS DNs to measurements of down-welling radiation. Due to the modification and up-grade of the NERC ***casi*** between flight seasons, the coefficients produced by this study (Appendices C. and D.) are only applicable to data calibrated with NERCCAL6. It has highlighted limitations with the methods and the ILS system. Finally, it has identified areas where further investigation is required to fully understand the calibration and operational use of the ILS.

7. ILS INTERCALIBRATION PROCEDURE

1. Location of ILS intercalibration site
    a. Availability of ground power for instruments
    b. Minimum of obstructions within the FOV of the instruments

2. Timing of ILS intercalibration experiments
    a. Availability of field spectrometer with calibrated cosine head
    b. Maximise radiation falling on reference panel and instruments
    c. Clear or uniformly hazy sky

3. Instrument set up
    a. Reference panel in centre of ***casi*** FOV surrounded by black out cloth
    b. Cosine head of field spectrometer located as close as possible to ILS

4. Data collection
    a. Concurrent measurements for approximately 5 minutes {possibly with a range of integration times}
    b. ***casi*** in spectral mode, 39 look directions in centre of the FOV, spaced every four pixels {possible manual dark current collection}
    c. Field spectrometer collecting measurements of down-welling irradiance at the highest temporal frequency

5. Data processing
    a. Field spectrometer measurements processed to average irradiance during data collection
    b. Average irradiance resampled to ***casi*** wavebands
    c. ***casi*** data processed to DNs with system offsets removed
    d. ILS data extracted from ***casi*** data and averaged during data collection

6. Calibration
    a. Calculate calibration coefficients between averaged ILS data and resampled average irradiance data
    b. Calculate correction coefficients between averaged ILS data and averaged panel radiance data
    c. Estimate coefficients of a curve to fit to calibration coefficients (if appropriate)

ACKNOWLEDGEMENTS

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APPENDICES

A. *SPECTRON COS-CONICAL CONFIGURATION AND OPERATION*

The Spectron Engineering Inc. SE590 Field-Portable Data-Logging Spectroradiometer (Spectron Engineering Inc., 1984; Milne *et al.,* 1988) is a light weight instrument suitable for rapid spectral surveys at visible and NIR wavelengths. The system consists of a CE500 controller and one or two CE390 optical heads.

The optical head collects radiation and disperses it, via a diffraction grating, across a silicon photodiode array. The 256 elements of the array simultaneously record a spectrum of radiation intensity in the 400 to 1100 nm wavelength range. The fore-optics of the head can either be a lens with a FOV between 1 and 20° or a cosine receptor and diffuser.

The optical head is connected by a single cable to the controller that contains a microprocessor and tape storage device. The controller commands the optical head, performs low-level processing on the data collected by the optical head and writes these data to the tape along with system information. The controller also allows data from tapes to be read back into the system for output directly to a computer. The whole system is powered by batteries connected to the controller.

When the collection of a spectrum is initiated, the controller commands the head to close a shutter in the optics and a measurement of dark current in made. The shutter is then opened and a spectrum collected to select the optimum integration time. The target spectrum to be recorded to tape is then collected with the selected integration time. The dark current spectrum is then removed from the target spectrum and the result is written to the tape.

For the spectral data collection in this study the Spectron was operated in cos-conical mode, where two optical heads were attached to the controller. One was downward pointing with a 15° lens to measure reflected radiation from the target or reference panel, while the other was upward pointing and fitted with a cosine receptor and diffuser for measuring the incoming radiation. In this mode the Spectron could quickly collect pairs of cosine and conical spectra for calibration to radiance and irradiance, or for combination to estimate surface reflectance.

Field measurements consisted of collecting a pair of cosine and conical spectra for each sample. Each of the recorded spectra were made up of an average of four individual spectra. A reference panel was used as the target at intervals during the data collection to allow the intercalibration of the cosine and conical heads for the estimation of reflectance.

The initial processing step was to download the spectra from the Spectron tapes, via the controller, to a computer running the `ibmspec` software. Once on the computer the spectra were processed by a suite of software written in ASYST (Rollin, 1994a; Rollin, 1994b). The Apertured-Cosine Intercalibration Routines (`cosmenu` and `cosbatch`) used the reference panel spectrum (*DNc*) and the cosine spectrum (*DNp*) to calculate an intercalibration spectrum (*AP*) as follows

$$AP_i = (DNp_i / DNc_i) * \rho p_i$$

where ρp was the reflectance of the reference panel and i is the waveband. The Primary Processing Routines (`smenu` and `sbatch`) contained a number of basic spectral processing functions, which included the combination of cosine and conical spectra to estimate reflectance and the calibration of spectra to radiance and irradiance. To estimate surface reflectance (ρs) a ratio of the conical spectrum (DNs) and the cosine spectrum were multiplied by the head intercalibration as follows

$$\rho s_i = (DNs_i / DNc_i) * AP_i$$

To calibrate to either radiance (L) or irradiance (E) the spectra were multiplied by a calibration coefficient (C) appropriate to the head being used as follows

$$L_i = DNs_i * Ccon_i$$

or

$$E_i = DNc_i * Ccos_i$$

The calibrated spectra were stored in ASCII format and loaded into spreadsheets for further processing.

B. RESAMPLING PROCEDURE

To compare spectra that were recorded by different instruments it was necessary to resample them spectrally to a common set of waveband centres. Software was written in IDL to resample spectra from any instrument to the wavebands centres used by the ***casi*** and in this case relative to the NERCCAL6 laboratory calibration. The software is based on a procedure written by Andrew Wilson (RSADU) to calculate the waveband centres and band widths of the 288 ***casi*** wavebands from the 'G' numbers produced by the laboratory calibration and coefficients supplied by Itres Research. The resampling procedure generates a Gaussian response function based on the waveband centre and the band width generated above. The response function is then convolved with the spectra to be resampled and integrated to give the measurement at the ***casi*** waveband. This procedure is then repeated for each ***casi*** waveband.

C. *CALIBRATION COEFFICIENTS DERIVED FROM SPECTRON IRRADIANCE DATA*

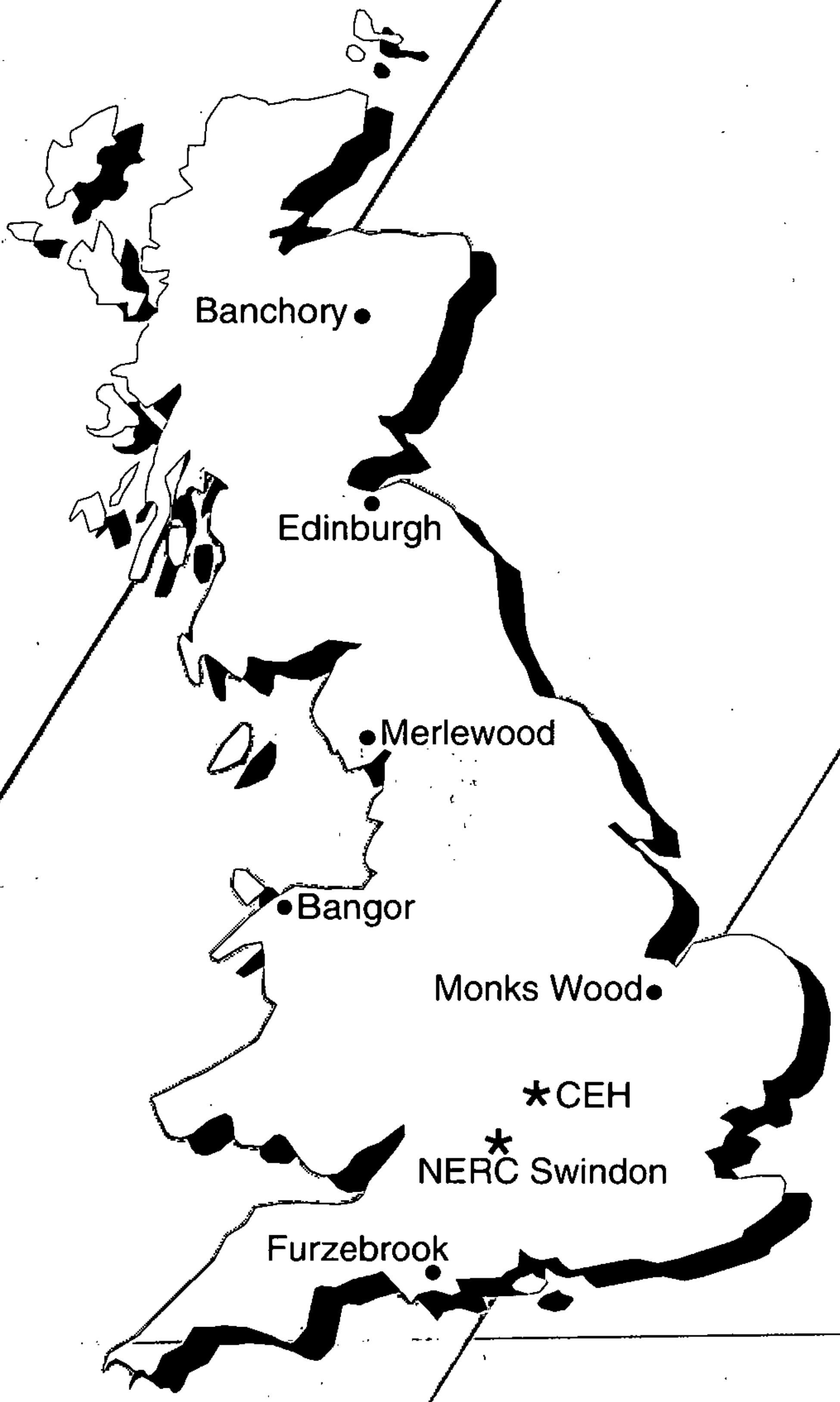
Wavl (nm)	Calibration coeff (*c*)	Wavl (nm)	Calibration coeff (*c*)	Wavl (nm)	Calibration coeff (*c*)	Wavl (nm)	Calibration coeff (*c*)
395.97	1.999	487.35	1.326	578.41	0.377	669.53	2.020
397.77	2.531	489.13	1.182	580.19	0.370	671.32	2.089
399.57	2.500	490.92	1.052	581.98	0.357	673.11	2.228
401.36	3.122	492.71	1.015	583.76	0.354	674.90	2.212
403.16	4.793	494.49	0.973	585.55	0.351	676.69	2.198
404.95	5.841	496.28	0.920	587.33	0.348	678.48	2.219
406.75	6.046	498.07	0.905	589.12	0.366	680.27	2.464
408.55	5.483	499.85	0.898	590.90	0.385	682.06	2.295
410.34	6.277	501.64	0.877	592.69	0.372	683.86	2.208
412.14	6.500	503.43	0.813	594.47	0.369	685.65	2.550
413.93	6.090	505.21	0.788	596.26	0.370	687.44	3.163
415.73	5.705	507.00	0.740	598.04	0.379	689.23	3.165
417.52	6.813	508.79	0.716	599.83	0.392	691.02	3.069
419.31	6.331	510.57	0.687	601.62	0.398	692.81	3.031
421.11	7.315	512.36	0.666	603.40	0.411	694.61	2.899
422.90	6.615	514.14	0.632	605.19	0.409	696.40	3.006
424.69	7.028	515.93	0.616	606.97	0.427	698.19	2.940
426.49	6.273	517.72	0.642	608.76	0.439	699.98	3.055
428.28	6.025	519.50	0.642	610.54	0.461	701.78	3.126
430.07	6.200	521.29	0.584	612.33	0.474	703.57	3.324
431.87	4.773	523.07	0.578	614.11	0.501	705.36	3.336
433.66	4.518	524.86	0.573	615.90	0.505	707.16	3.468
435.45	4.233	526.64	0.573	617.69	0.532	708.95	3.232
437.24	3.673	528.43	0.572	619.47	0.523	710.75	3.511
439.03	3.438	530.21	0.532	621.26	0.550	712.54	3.084
440.82	3.393	532.00	0.508	623.05	0.575	714.33	3.381
442.62	3.127	533.78	0.525	624.83	0.589	716.13	3.285
444.41	2.840	535.57	0.487	626.62	0.622	717.92	3.398
446.20	2.493	537.35	0.484	628.41	0.661	719.72	3.338
447.99	2.347	539.14	0.468	630.19	0.699	721.52	3.454
449.78	2.209	540.93	0.470	631.98	0.734	723.31	3.452
451.57	2.268	542.71	0.454	633.77	0.746	725.11	3.713
453.36	2.325	544.50	0.442	635.55	0.796	726.90	3.200
455.15	2.200	546.28	0.430	637.34	0.838	728.70	3.531
456.94	2.035	548.07	0.423	639.13	0.870	730.50	2.968
458.73	2.193	549.85	0.421	640.91	0.924	732.29	3.167
460.52	2.112	551.64	0.410	642.70	0.982	734.09	2.771
462.31	1.925	553.42	0.413	644.49	1.050	735.89	2.826
464.10	1.916	555.20	0.401	646.28	1.145	737.69	2.857
465.89	1.851	556.99	0.402	648.07	1.239	739.49	2.886
467.68	1.881	558.77	0.404	649.85	1.282	741.28	3.155
469.46	1.877	560.56	0.404	651.64	1.250	743.08	2.735
471.25	1.790	562.34	0.392	653.43	1.400	744.88	2.903
473.04	1.768	564.13	0.388	655.22	1.425	746.68	2.643
474.83	1.688	565.91	0.391	657.01	1.715	748.48	2.526
476.62	1.615	567.70	0.390	658.80	1.623	750.28	2.275
478.41	1.537	569.48	0.386	660.58	1.659	752.08	2.082
480.19	1.484	571.27	0.392	662.37	1.691	753.88	2.210
481.98	1.390	573.05	0.378	664.16	1.796	755.68	1.989
483.77	1.327	574.84	0.371	665.95	1.941	757.48	1.921
485.56	1.273	576.62	0.374	667.74	2.000	759.28	2.189

Wavl (nm)	Calibration coeff (c)	Wavl (nm)	Calibration coeff (c)
761.09	3.542	853.44	1.433
762.89	4.307	855.26	1.475
764.69	3.443	857.09	1.393
766.49	2.559	858.91	1.375
768.30	2.017	860.73	1.418
770.10	1.831	862.55	1.451
771.90	1.960	864.38	1.444
773.71	1.918	866.20	1.479
775.51	1.901	868.03	1.527
777.32	1.843	869.85	1.461
779.12	1.771	871.68	1.413
780.93	1.951	873.50	1.449
782.73	1.718	875.33	1.511
784.54	1.729	877.16	1.431
786.34	1.805	878.99	1.366
788.15	1.919	880.81	1.424
789.96	1.909	882.64	1.395
791.76	1.733	884.47	1.340
793.57	1.830	886.30	1.324
795.38	1.658	888.13	1.475
797.19	1.613	889.96	1.411
799.00	1.723	891.79	1.383
800.81	1.700	893.62	1.499
802.62	1.719	895.46	1.545
804.43	1.781	897.29	1.585
806.24	1.592	899.12	1.674
808.05	1.610	900.95	1.602
809.86	1.497	902.79	1.463
811.67	1.604	904.62	1.453
813.48	1.574	906.46	1.523
815.29	1.566	908.29	1.833
817.11	1.651	910.13	3.678
818.92	1.645	911.97	5.400
820.73	1.664		
822.55	1.612		
824.36	1.450		
826.17	1.438		
827.99	1.534		
829.80	1.568		
831.62	1.495		
833.44	1.442		
835.25	1.437		
837.07	1.390		
838.89	1.409		
840.71	1.442		
842.52	1.420		
844.34	1.481		
846.16	1.424		
847.98	1.487		
849.80	1.573		
851.62	1.553		

D. *CORRECTION COEFFICIENTS DERIVED FROM REFERENCE PANEL DATA*

Wavl (nm)	Calibration coeff (*c*)	Wavl (nm)	Calibration coeff (*c*)	Wavl (nm)	Calibration coeff (*c*)	Wavl (nm)	Calibration coeff (*c*)
395.97	0.632	487.35	0.346	578.41	0.102	669.53	0.560
397.77	0.782	489.13	0.322	580.19	0.103	671.32	0.575
399.57	0.711	490.92	0.284	581.98	0.102	673.11	0.614
401.36	0.805	492.71	0.274	583.76	0.103	674.90	0.614
403.16	1.112	494.49	0.271	585.55	0.100	676.69	0.615
404.95	1.272	496.28	0.257	587.33	0.100	678.48	0.627
406.75	1.260	498.07	0.246	589.12	0.096	680.27	0.706
408.55	1.139	499.85	0.244	590.90	0.107	682.06	0.669
410.34	1.301	501.64	0.233	592.69	0.105	683.86	0.653
412.14	1.352	503.43	0.221	594.47	0.103	685.65	0.673
413.93	1.275	505.21	0.223	596.26	0.105	687.44	0.761
415.73	1.194	507.00	0.207	598.04	0.107	689.23	0.754
417.52	1.436	508.79	0.203	599.83	0.110	691.02	0.803
419.31	1.375	510.57	0.195	601.62	0.111	692.81	0.831
421.11	1.608	512.36	0.189	603.40	0.116	694.61	0.813
422.90	1.476	514.14	0.176	605.19	0.116	696.40	0.851
424.69	1.582	515.93	0.168	606.97	0.121	698.19	0.828
426.49	1.398	517.72	0.164	608.76	0.123	699.98	0.844
428.28	1.215	519.50	0.178	610.54	0.128	701.78	0.861
430.07	1.305	521.29	0.167	612.33	0.131	703.57	0.925
431.87	1.114	523.07	0.163	614.11	0.138	705.36	0.942
433.66	1.070	524.86	0.167	615.90	0.137	707.16	0.986
435.45	1.045	526.64	0.151	617.69	0.147	708.95	0.931
437.24	0.844	528.43	0.164	619.47	0.148	710.75	1.025
439.03	0.807	530.21	0.154	621.26	0.156	712.54	0.914
440.82	0.849	532.00	0.144	623.05	0.161	714.33	0.998
442.62	0.789	533.78	0.148	624.83	0.163	716.13	0.911
444.41	0.693	535.57	0.142	626.62	0.172	717.92	0.885
446.20	0.624	537.35	0.137	628.41	0.177	719.72	0.888
447.99	0.596	539.14	0.132	630.19	0.189	721.52	0.946
449.78	0.580	540.93	0.129	631.98	0.201	723.31	0.966
451.57	0.561	542.71	0.128	633.77	0.207	725.11	1.020
453.36	0.572	544.50	0.127	635.55	0.221	726.90	0.872
455.15	0.553	546.28	0.123	637.34	0.235	728.70	0.967
456.94	0.514	548.07	0.120	639.13	0.244	730.50	0.834
458.73	0.545	549.85	0.121	640.91	0.256	732.29	0.920
460.52	0.539	551.64	0.118	642.70	0.274	734.09	0.818
462.31	0.494	553.42	0.118	644.49	0.294	735.89	0.839
464.10	0.478	555.20	0.117	646.28	0.317	737.69	0.844
465.89	0.458	556.99	0.114	648.07	0.340	739.49	0.853
467.68	0.474	558.77	0.112	649.85	0.353	741.28	0.938
469.46	0.467	560.56	0.114	651.64	0.349	743.08	0.822
471.25	0.464	562.34	0.111	653.43	0.392	744.88	0.885
473.04	0.455	564.13	0.110	655.22	0.373	746.68	0.814
474.83	0.435	565.91	0.109	657.01	0.445	748.48	0.791
476.62	0.417	567.70	0.111	658.80	0.447	750.28	0.736
478.41	0.407	569.48	0.107	660.58	0.467	752.08	0.711
480.19	0.401	571.27	0.107	662.37	0.475	753.88	0.810
481.98	0.382	573.05	0.107	664.16	0.504	755.68	0.765
483.77	0.360	574.84	0.103	665.95	0.542	757.48	0.603
485.56	0.301	576.62	0.103	667.74	0.557	759.28	0.525

Wavl (nm)	Calibration coeff (c)	Wavl (nm)	Calibration coeff (c)
761.09	0.596	853.44	0.529
762.89	0.704	855.26	0.550
764.69	0.791	857.09	0.525
766.49	0.728	858.91	0.529
768.30	0.655	860.73	0.543
770.10	0.623	862.55	0.553
771.90	0.667	864.38	0.553
773.71	0.647	866.20	0.570
775.51	0.634	868.03	0.593
777.32	0.611	869.85	0.575
779.12	0.587	871.68	0.565
780.93	0.649	873.50	0.584
782.73	0.573	875.33	0.612
784.54	0.578	877.16	0.584
786.34	0.602	878.99	0.562
788.15	0.640	880.81	0.590
789.96	0.635	882.64	0.583
791.76	0.577	884.47	0.568
793.57	0.614	886.30	0.569
795.38	0.562	888.13	0.639
797.19	0.550	889.96	0.611
799.00	0.590	891.79	0.591
800.81	0.585	893.62	0.624
802.62	0.598	895.46	0.626
804.43	0.630	897.29	0.639
806.24	0.571	899.12	0.686
808.05	0.585	900.95	0.668
809.86	0.539	902.79	0.619
811.67	0.560	904.62	0.626
813.48	0.533	906.46	0.665
815.29	0.518	908.29	0.799
817.11	0.548	910.13	1.603
818.92	0.540	911.97	2.348
820.73	0.561		
822.55	0.556		
824.36	0.499		
826.17	0.498		
827.99	0.537		
829.80	0.546		
831.62	0.525		
833.44	0.513		
835.25	0.517		
837.07	0.506		
838.89	0.517		
840.71	0.532		
842.52	0.528		
844.34	0.552		
846.16	0.531		
847.98	0.554		
849.80	0.576		
851.62	0.568		



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