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APPENDIX I – INTRODUCTION TO CASI AND ALTM DATA

CASI (Compact Airborne Spectrographic Imager) is a passive sensor recording reflected radiance in visible and near-infrared wavelengths (400-915nm). Operating in 'spatial mode', CASI records continuous coverage across a 512 pixel swath in up to 19 bands of selected spectral location and width (Babey and Anger 1993). The spatial resolution of CASI imagery (i.e. pixel size) depends on lens optics and aircraft altitude during image acquisition. A 3m spatial resolution was agreed for the CASI data in this project, as this would enable detection of linear and point features (such as hedges and trees) while allowing coverage at a modest data rate commensurate with later potential operations. With mosaic-coverage, a 3m pixel size required 4 flight-lines to cover each target site. The configuration of the sensor adopted the narrowest possible lens to minimise off-nadir viewing affects which would otherwise cause adverse geometric distortions, topographic displacements and illumination differences when illumination was across-track. The chosen wavebands were those of the VEG bandset (Table 7), used in earlier work for the then National Rivers Authority (Fuller *et al.* 1995a & b). It was based on the 14 waveband BIOTA bandset adopted by CEH for coastal work (Thomson *et al.* 1998), modified for inland use to give more data around the red-infrared boundary that could be used for red-edge modelling in biomass estimations of vegetation.

Ch.	Centre/Width (nm)		Start nm (Ch No.)		End nm (Ch No.)
1.	450	20	441.53 (264)	-	459.17 (254)
2.	490	20	480.37 (242)	-	499.84 (231)
3.	552	10	547.74 (204)	-	556.63 (199)
4.	670	10	665.57 (138)	-	674.54 (133)
5.	700	10	694.28 (122)	-	703.27 (117)
6.	710	10	705.07 (116)	-	711.06 (111)
7.	740	10	735.66 (99)	-	744.67 (94)
8.	750	7	746.47 (93)	-	753.68 (89)
9.	762	5	760.90 (85)	-	764.51 (83)
10.	780	10	775.34 (77)	-	784.37 (72)
11.	820	10	815.13 (55)	-	824.18 (50)
12.	865	10	860.46 (30)	-	869.54 (25)

Table 7. The selected CASI bandsets

The ALTM (Airborne Laser Terrain Mapper) uses a pulsed laser to provide a ranging measurement by determining the time-of-flight between an emitted and received pulse following diffusion and reflection from a feature on the earth surface (Flood and Gutelius 1997). To identify the 3-D position of each ranged point, the LIDAR is supported by an integrated position and orientation system (POS) consisting of a differential global positioning system and an inertial measurement unit (Wehr and Lohr 1999). The ALTM scans across the swath generating a saw-toothed pattern of spot heights whose spacing is dictated by the laser pulse repetition rate, scan angle, aircraft speed and height, and terrain topography (Ackermann 1999). Each incident laser pulse supplies the altitude for the ground surface or objects on it. Any vegetated surface will return a multiple echo, as the laser pulse can penetrate into and possibly through the vegetation cover. Typically the first significant echo pulse records information from the vegetation canopy surface, whilst the last significant echo pulse records ground or within-canopy information, depending on the canopy density

(Ackermann 1999, Davenport *et al.* 2000). The ALTM 1020 supplies only 'first' or 'last' pulse data, and so for the purposes of this project 'first' pulse data were recorded to supply vegetation canopy information. An average point distribution of 2.5m was selected to achieve a level of spatial detail commensurate with the CASI data. The laser pulse 'footprint' was *ca*. 0.2m at nadir.

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APPENDIX II - FIELD SITE SELECTION

The original criteria which determined the selection of field sites were:

- There will be 4 trial squares plus 4 check squares, a pair of each in Arable, Pastural, Marginal and Upland Landscapes.
- Each site must cover 3 km x 3 km, centred on a 1 km field survey square.
- The squares should be located close together to be within 20 km of a GPS base station.
- The majority of each 3 km x 3 km site (not just the central square) should be representative of the chosen Landscape.

To select squares, we first interrogated the Countryside Information System database using a 5 km x 5 km potential study site, to determine the number of neighbouring 1 km squares, out of 24 possibles, which shared the same Landscape class as the core field survey square. We then plotted those sites where over 15 representative squares would be found out of 25. Inspection showed that it was not possible for one 40 km circle to encompass all 4 Landscapes; but it was possible to select examples, each with *ca* 20 representative squares per site, if we used TWO general study areas. One group of squares in east Cumbria represented Upland and Marginal land (each with 2 sites): none had significant content of urban land. There were three options for combined Arable and Pastural areas; in Berkshire, Gloucestershire and Wiltshire/Avon: the first two contained high contents of urban/suburban (perhaps averaging 25-30%); the Wiltshire/Avon urban cover was 0-20% with an average of *ca* <10%. The selected squares are shown in Table 8.

Landscape type	**CS 2000 number**	**County**	**No. of squares in same Landscape**		**Trial / Check square**
Arable	180	Wiltshire	9/9	22/25	T
Arable	209	Wiltshire	9/9	25/25	C
Pastural	208	Avon	9/9	25/25	T
Pastural	179	Avon	7/9	19/25	C
Marginal	692	Cumbria	9/9	24/25	T
Marginal	691	Cumbria	9/9	25/25	C
Upland	708	Cumbria	9/9	25/25	T
Upland	1214	North Yorks	9/9	25/25	C

Table 8. The Countryside Survey squares chosen as representative of their Landscape types.

APPENDIX III – DATA COLLECTION

1. Airborne remotely sensed data

The CASI and ALTM data were acquired initially during summer 1998, to coincide with the field survey. However, data quality problems arose because of poor weather conditions and instrument failure during summer 1998. Also the required data standards of this project exceeded those for normal operational purposes of the EA. After consultation with the EA all eight sites were re-flown with both CASI and ALTM during summer 1999. Flying dates for the CASI data were 25th June for the Arable and Pastural sites, and 26th July for the Marginal and Upland sites. The ALTM was flown on 8th and 17th June for the Arable/Pastural and Marginal/Upland sites respectively. The specifications for airborne data retrieval were that at least a 3 x 3 km area was recorded for each site, from which the central CS2000 square could be extracted. The ALTM recorded first pulse only, capturing height information for the tops of vegetation canopies. A slight edge-of-flight-line z-displacement was detected in the ALTM data, particularly of the Marginal/Upland sites. The CASI recorded twelve wavebands, which focused particularly on the red and near infrared spectral boundary, with a pixel size of 3 m. The atmospheric quality was excellent and the geometric quality was as good as the EA systems would allow.

Pre-processing of the 1999 CASI data at the EA involved roll-correction only for flight-lines covering the Arable, Pastural, and Marginal squares. This was because of a problem in their Itres 'geocor' software, which generated erroneous data shifts if applied to the CASI imagery for geometric correction. For the Arable, Pastural, and Marginal sites, the CASI data supplied by the EA thus contained residual geometric distortions where aircraft roll had been either under- or over-compensated. In addition, geometric distortions also resulted from underlying topography, which was not accounted for in the pre-processing. The two Upland squares, however, were given higher order geometric conversion, as conventional geometric correction of imagery can be a near impossible process in upland areas, where fewer prominent landmarks (e.g. field boundaries, crossroads) are found.

2. Field reconnaissance

Field visits were made to all eight sites during summer 1998 to coincide with the timetables of the CS 2000 field surveyors. Thus, these took place in the weeks beginning 13th July for the Marginal and Upland sites and 14th September for the Arable and Pastural sites. At both locations the field visits were contemporaneous with CS 2000 surveying for three of the four CS squares. This minimised the level of disturbance to land owners resulting from this study, and enabled first-hand experience to be gained on the issues and problems faced by field surveyors in all four landscape types. The field visits were designed to complement the field survey, providing additional information. The focus at all sites was thus on identifying land-cover patterns and features in the eight 1 km squares surrounding the CS square, so as to identify additional cover types not present in the central 1 km square. (Although acquired for all 8 sites, subsequent limitations on airborne data processing resulted in only 3x3 km field data being used for only one site).

In addition to the land-cover information, hedgerow and tree height measurements were recorded at one site to provide comparison with the airborne height data. A detailed 150m hedge profile was recorded, with height and width at 3m intervals and the dimensions of gaps and trees also recorded.

Repeat field visits were made to the Arable and Pastural sites during the week beginning 19th July 1999 to acquire ground reference information for the replacement airborne data. This field work focussed primarily on the central 1km square to identify any land-cover change from 1998. The Marginal and Upland sites were not re-surveyed owing to time constraints since it was considered that only arable land-cover types were likely to show significant changes.

APPENDIX IV – IMAGE PROCESSING METHODS

A processing flow-line has been developed at CEH that involves: elevation and height data generation from ALTM point sample data; CASI normalisation, geometric correction and segmentation; image classification; and knowledge-based correction. The methods, training statistics and correction rules were developed using the trial squares (CS Squares 180, 208, 692, and 708) which were selected by virtue of image data quality and land-cover diversity. The test of the operational capabilities of the processing flow-line was in its application to the check squares. Of interest was the wider applicability of the techniques and of variables such as segmentation thresholds, classification training data, and KBC rules.

1. ALTM data pre-processing

1.1 Creating a Digital Surface Model

The ALTM data were supplied by the EA as ascii files of *x*, *y*, *z* point information. The point sample information formed a zig-zag pattern with distribution varying, but typically falling *c.* 3-4 m apart. The ALTM swath width was approximately 750 m, and the flight-lines were flown to overlap. A 1 km square contained around 165000-175000 sample points.

The first stage of the ALTM pre-processing was to interpolate a continuous surface from the point sample information. This was achieved by the creation of an irregular triangular mesh (Triangulated Irregular Network) from the sample points. This was then transformed into a lattice with a rectangular array of mesh points with a chosen constant sampling interval in the *x*- and *y*- direction of 1m. Because the ALTM data were first response only, this 1 m spatial resolution interpolated grid was a Digital Surface Model (DSM), as trees, buildings, etc, were present in the data with height expressed in metres above OS Datum (OSGB 1936).

1.2 Creating a Digital Elevation Model

The second, and more complicated phase of ALTM pre-processing, was the generation of a Digital Elevation Model (DEM) in which all prominent superficial features (e.g. trees, hedges, buildings) were removed to give landscape elevation. To achieve this, all superficial features had to be removed from the DSM to allow re-interpolation of surface elevation across the gaps generated. Various methods of feature removal were investigated including: the use of surface variance filters; and the mean filtering and statistical approach recommended by Jaafar *et al.* (1999). These approaches identified variance in surface height and in mean surface height respectively, over a specified area using a spatial filter. The size of the spatial filter had to be determined statistically for each image, depending on the nature of landscape and surface feature variance. Once the appropriate filter size had been decided, a threshold was identified to distinguish between pixels representing the ‘ground’ and those which represent unwanted features such as buildings. In the approach using height variance filters, the threshold was applied directly to the resultant image, whilst in the approach using mean filtering, the threshold was applied to the product of subtracting the filtered image from the DSM. In general, the variance filtering approach identified the edges of features such as hedges or buildings, whilst the mean filtering approach masked the centre of features. An additional stage was to ‘grow’ a mask outwards to capture a greater proportion of the unwanted surface features, or to use the two methods together to identify both the centre and edges of features. However, these approaches were found to achieve the complete removal of surface features (such as hedges and buildings) at the expense of removing considerable areas of near-ground hits in areas of low growth vegetation. This influenced the potential accuracy of the surface interpolation across the masked areas, especially large blocks of woodland that contain areas of near-ground sampling in glades and rides.

Interpolation of heavily masked ALTM data did, however, give a rough indication of the ground surface. This was used to put surface elevation information back into the original masked image, where the difference between the original DSM and interpolated surface were within a specified limit (e.g. + or - 0.5 metres). This enabled the creation of a mask which removed virtually all unwanted surface features (such as hedges and buildings) but considerably fewer true ground samples.

The method of interpolating across the masked off data gaps was selected from an operational standpoint. Possible procedures included: triangulation, splining, kriging and inverse distance weighted methods of interpolation. Of these, surface triangulation was the preferred choice since it represented a continuation of the method used to create the original DSM from the ALTM point sample data. In addition, the other interpolation methods proved highly intensive on computer and analyst time to identify the optimum input parameters, which varied spatially depending on the nature of the landscape.

1.3 Creating a surface height model and other products

Once the Digital Surface and Elevation Models were complete, it was a simple task to create relative height data for surface features by subtracting the two data-sets. In addition, slope and aspect data were generated directly from the DEM.

Height data were generated only for Arable, Pastural and Marginal squares, since no features with significant above ground height occurred in the Upland sites. The accuracy of the surface height data was examined in Square 208 by comparing tree height estimates, derived using the 1999 ALTM data and measurements taken in the field in 1998. Correspondence in height estimates was found to vary between 5 cm and 90 cm. It should be noted that because of the slight z-displacement in the ALTM data, a degree of manual editing was necessary to ‘clean’ the surface height imagery.

2. CASI image pre-processing

2.1 Image normalisation

In optical imagery, the spectral signal recorded for surface features will be ‘distorted’ by atmospheric effects of scattering and absorption. The degree of atmospheric distortion in an image will vary with atmospheric conditions, and with both view and sun angle. Atmospheric attenuation needs to be accounted for to achieve comparability in spectral reflectance of features across image flight-lines, or of areas sampled at different times or dates. Achieving this by detailed atmospheric modelling is far beyond the scope and time-frame of this project and, to-date, no generalised atmospheric correction model exists for airborne imagery. For operational purposes (in the absence of atmospheric correction models), it would be necessary to visit each site at the time of airborne data acquisition to record calibration reflectance data for target surface features. Given the spatial coverage of these trial data-sets, it is virtually impossible to find surface features within or between sites that should have identical surface reflectance spectra, since building materials, crop maturity, grassland nutrient status, and semi-natural land-cover mosaics, will all vary spatially.

It was possible, however, to perform some basic normalisation procedures. For example, a procedure for correcting view angle differences across the swath has been devised at CEH based on mean nadir values. In this procedure normalised pixel values were calculated as follows:

$$x'_{ij} = x_{ij} - (\overline{x}_j - \overline{x}_{nadir})$$

where x_{ij} was the original pixel value at row i and column j, $\overline{x}_j$ was the average of column j after smoothing using a moving average (100 pixels) and $\overline{x}_{nadir}$ was the average of the nadir column after smoothing. The radiance values of adjacent flight lines could be made comparable by normalising each to the mean scene values of the central flight line for each site, and the same approach could be used to normalise between sites of the same Landscape type. However, since an inherent assumption in this procedure was that the type and proportions of land-cover were similar between flight-lines and different sites, there was a limit to the degree to which normalisation could be performed. This restricted the assumed transferability of identified spectral characteristics. Thus, the 1999 CASI data of the Arable and Pastural sites (which have a mixture of grassland and agriculture land-covers) were normalised to enable their combined training and classification. For the Marginal sites, however, the check square was normalised to the trial square, whilst for the Upland sites the land-cover was too distinct to allow the normalisation of the check to the trial square.

2.2 Geometric correction

Correction of the CASI imagery was necessary to remove geometric distortions remaining in the data following pre-processing by the EA. This was achieved by registering the required sections of each CASI flight-line to the matching DSM by identifying ground control points (GCPs) and performing 'rubber sheeting' to warp the image around those identified points. This was an extremely labour intensive process, requiring anything up-to 200 GCPs to correct a 1 km square. Furthermore, because only the specified control points were guaranteed to link the ALTM and registered CASI imagery, it was virtually impossible to achieve a perfect correspondence. Registration was performed using a nearest neighbour algorithm, resampling the CASI imagery to match the 1 m spatial resolution of the elevation data. This method had the advantage of maintaining the original spectral value of pixels whilst achieving a more detailed spatial matching by sub-dividing each 3 m CASI pixel. It must be remembered, however, that the minimum mappable unit will not be reduced in size by this apparent increase in image spatial resolution.

For many of the sites (Squares 179, 180, 208, 209 and 691), the central 1 km square did not fall entirely within one flight-line but was split across two adjacent runs. In these circumstances, the registered flight-line sections had to be mosaicked to generate a single data-set.

2.3 Topographic-illumination correction

An additional stage in the processing flow-line was investigated during the check square analysis. Topographic variation influences the spectral response of ground features recorded in CASI imagery. This is because undulating terrain is illuminated differentially according to whether facets of terrain are horizontal, face the sun, or face away from the sun (potentially shaded from direct solar illumination). Only in the case of the Marginal check square was the nature of relief in the central 1 km square considered significant enough to warrant attempted topographic-illumination correction. This was carried out using software developed by Cambridge University Geography Department and used operationally in creating the Land Cover Map 2000 (Fuller *et al.* 1999a). Differential illumination across the landscape, and its consequent effects on the radiation recorded by the CASI sensor, were modelled using a smoothed version of the DTM and compensated for in the topographic correction software.

2.4 Image segmentation

The image segmentation procedure was based on the same software package being used in LCM2000 (Fuller *et al.* 1999b). Written originally in the Microsoft Windows environment by the Cambridge University Geography Department, Laser-Scan has now implemented a fully operational version of the segmentation software, in a Unix environment.

Important methodological issues for image segmentation include:

- band selection for edge-detection and segmentation,
- setting thresholds to identify edges and generate segments,
- post-segmentation boundary rejection and generalisation.

It was only possible to use three bands for the edge-detection / segmentation process and so the optimum choice of wavebands was investigated using the four trail 1 km squares of 1999 CASI data. Principle Components Analysis of the 12-band CASI images, demonstrated these data to be two-dimensional (with at least 96% of variance contained in PCs 1 and 2). The two dimensions related to the visible and near infrared (NIR) part of the spectrum. Correlation analysis supported these findings, with strong positive correlations within, but not between, the visible and NIR wavebands. In spite of the strong 2-dimensionality of the data-set, it was decided that out of the 12 available wavebands, the three bands which made the strongest contribution to PCs 1-3 and which were the least correlated were Bands 4, 6, and 10. These occupy a point of maximum red absorption by vegetation (670 nm), a point along the so-called ‘red-edge’ (708 nm) between the red absorption trough and NIR reflectance peak, and a point in the NIR vegetation reflectance maximum (780 nm). The segmentation algorithm was tested using PCs 1-3 and CASI Bands 4, 6 and 10, in the four Landscape types. This demonstrated the use of individual wavebands to give a better result, with more ‘meaningful’ parcels created.

The segmentation procedure builds parcels around ‘seed-points’ that have been selected as within a segment or a land parcel; an edge detector is used to ensure that the appropriate seed-points are selected away from parcel-edges. There is potential in the software to dictate the degree of region merging by setting segmentation thresholds for each of the spectral bands and by establishing the number of standard deviations expected to contain the majority of the population of a segment. If the first threshold (entered separately for each band) was set low (i.e. 1 SD) then a higher number of segments was generated initially. If the second threshold was then set high (i.e. 6 SDs in the farmed Landscape types and 3 SDs in the Uplands) a much greater level of region merging took place. This gave a much better end-product than growing bigger parcels initially, as more detail was retained without generating an overly segmented image.

Post-segmentation generalisation involved dissolving parcels of 9 or less pixels (i.e. one pixel of data in the raw CASI image) into the surrounding parcels. Sliver parcels greater than 9 pixels in size occurring at boundaries were, however, retained since linear features were very much a part of the CASI data.

It is important to note that this was a low-level segmentation process (Haralick & Shapiro, 1985) in that the parcels created were not necessarily meaningful entities (such as fields) but merely parts of them. The parcels were identified according to spectral variation which may have related, for example, to crop development, wind damage or unplanted field margins.

Once acceptable segmentations were achieved, vector versions were created in a GIS database. This was a simple procedure of raster-to-vector conversion where the boundaries between segments with different values in the raster images were represented by vector lines. These formed the basis of the vector data-base used in the classification procedure.

3. Airborne data classification

The classification approach was a per-parcel procedure based on CLEVER-Mapping (Smith & Fuller 1998, 2001), using the vector boundaries derived from the segmentation procedure and the full 12-band CASI images. Due to restrictions of the software package, a 16-bit to 12-bit conversion of the imagery was required. This reduced the dynamic range of the spectral values recorded, but maintained the relative differences between landscape features.

The classification was trained by assigning a class value to selected parcels of known land-cover types (Table 9). For the trial squares, this made use of detailed data from the Field Assessment Booklets and from personal visits to the sites during 1998 and 1999. Training was carried out separately for the following 1 km CASI data-sets: Arable trial square (1998 CASI data); Arable and Pastural trial squares (1999 CASI data); Marginal trial square (1999 CASI data); and Upland trial square (1999 CASI data). Only in the case of the Arable and Pastural squares in 1999 CASI data, was land-cover distribution considered similar enough to enable between-site spectral normalisation. The total array of spectral sub-classes identified across the 1km squares is shown in Table 10. These could be readily amalgamated into Broad Habitats, with the one exception of BH 3 (Boundary and linear features) which was trained for classification into its constituent parts of hedges and built surfaces.

The basic aim of the training procedure was to identify as much spectral variance within the image as possible, and to achieve this for each land-cover type present (i.e. to achieve a full and accurate sub-division of the spectral feature space). Because of the nature of the segmentation process, the parcels available for training varied in size, but were reasonably consistent in spectral variance. The important consideration in creating a training data-set was therefore not achieving an equal distribution of parcel size, but achieving an even distribution of training parcels throughout the spectral feature space.

Having identified a series of training parcels, it was then necessary to review the training data to decide on the spectral sub-classes to be used for classification. A refinement built into IGIS operation (as part of the LCM2000) allowed ‘image chips’, representing the remotely sensed data for each training area, to be displayed side-by-side on the screen, almost like a colour-chart. This enabled the training parcels to be compared and labelled to give a series of different spectral sub-classes where necessary (Kershaw and Fuller, 1992). The training areas were reviewed in what was considered to be the two most useful 3-band combinations (Bands 4, 3, 2 and Bands 10, 6, 4) to ensure that the spectral sub-classes were not mixed. When deciding on the aggregation of training parcels, the general rule applied was that the narrower range of spectral variance allowed in each spectral sub-class, the less likely would be confusion in classification at the aggregate level. For example, 11 sub-variants of bog were identified in the classification of the Upland trial square.

The classification procedure used the Maximum Likelihood algorithm (Schowengerdt 1997) applied to the parcel, using mean statistics to select the most likely class in statistical terms. The parcel statistics were extracted from a shrunken area (by a margin of 3 pixels) to avoid edge pixels with a mixed signature.

Land-cover Class	Arable Trial square		Pastural trial square	Marginal trial square	Upland trial square
	1998 data	1999 data	1999 data	1999 data	1999 data
Arable bare	X	X	X	X	-
Arable barley	X	X	-	-	-
Arable harvested	X	X	-	X	-
Arable kale	X	-	-	-	-
Arable linseed	-	X	-	-	-
Arable maize	-	X	X	-	-
Arable peas	X	-	-	-	-
Arable rape	-	X	-	-	-
Arable set-aside	X	-	-	-	-
Arable turnips	X	-	-	-	-
Arable wheat	X	X	X	-	-
Grassland – improved	X	X	X	X	-
Grassland – neutral	X	X	X	X	-
Grassland – acid	-	-	-	X	X
Coniferous woodland	X	X	-	-	-
Deciduous woodland	X	X	X	X	-
Deciduous hedge	X	X	X	X	-
Dwarf shrub heath	-	-	-	-	X
Fen, marsh, swamp	-	-	-	X	-
Bog	-	-	-	-	X
Built surface	X	X	X	X	-
Water	X	X	-	X	-
Shadow	X	X	X	X	-

Table 9 Land-cover types identified (X) in each trial 1 km square. (Note each of these land-cover types may be composed of several spectral sub-classes)

Landscape type	No. of parcels	No. of spectral sub-classes	No. of land-cover types	No. of Broad Habitats
Arable (1998 data)	103	41	16	7
Arable & Pastural	200	59	15	7
Marginal	139	40	11	8
Upland	63	17	3	3

Table 10. Breakdown of the training data used for the classification of the trial squares. (Note that the Arable and Pastural Squares in 1999 CASI data were trained and classified together.)

4. Knowledge-based correction

A degree of mis-classification of parcels was expected due to spectral similarities between certain land-cover types. Likely inter-class confusion could be estimated prior to classification from the review of training data. For example, the three grassland types in the four trial sites (improved, neutral and acid) showed spectral overlap with each other, and with sunlit aspects of deciduous woodlands / hedges, and with certain crop types (e.g. oilseed rape, peas, maize, barley) depending on crop maturity. The shaded aspects of deciduous woodlands / hedges showed spectral overlap with mature arable wheat, marsh / swamp, water, and shadow; whilst built surfaces showed spectral overlap with the arable classes of bare, harvested, and set-aside. Since shadows can be cast over any land-cover type present within a square, this class had a wider spectral range and showed overlap with more land-cover classes than the other spectral sub-classes.

Knowledge-based correction (KBC) procedures were required to address these classification errors, and have been developed using a combination of context, ALTM height data, CS 1990 codes, and class probabilities. Because the correction procedures operated per-parcel, more subtle internal context rules could be used (e.g. assigning parcels to adjoining or nearby classes).

4.1 Phase-1 KBC procedure

The simplest KBC rules devised were contextual, based on a parcel being surrounded by an unlikely land-cover type (Table 11). To give some examples, an arable parcel surrounded by built surfaces was relabelled as built, whilst a shade parcel surrounded by deciduous woodland was coded as deciduous. It must be remembered that, although the parcels reflect genuine spectral variance from ground features, they do not necessarily represent whole objects. Thus, fields were composed of many parcels, and so the KBC rules operated at the within-field level. Changes to parcel class assignment through the KBC process were applied at the level of land-cover types within the Broad Habitats. Thus in an arable setting, class re-assignment would be to an individual crop type.

The ALTM height data was invaluable at addressing mis-classification between the deciduous woodland / hedge classes and certain grassland and arable classes. It was possible to identify a height threshold, which all parcels classified as hedge or woodland must exceed, and all other parcels (except for built surface) must be under. Conversion to deciduous woodland / hedge classes was a simple matter, but conversion from deciduous woodland / hedge to neighbouring land-cover classes was according to local context and a series of class priority rules.

The CS 1990 reporting codes (and obviously the CS 2000 codes in any repeat exercise) represent an important data source that could be used in the KBC process. However, using these data for full knowledge-based correction would remove any ability to identify change by the classification of airborne imagery. Exceptions to this are the more stable classes such as roads, railways and built up areas, which are highly unlikely to be converted into agricultural use, grassland, forestry or semi-natural vegetation. Thus, a mask of CS 1990 reporting classes 51-52 (Railway and Road) and classes 53-55 (Built on land) was applied to identify and re-assign parcels mis-classified as arable (bare, maize, harvested), shadow, or water. From an operational standpoint, this correction can only be applied to Countryside Survey squares for which previous field survey data exist.

Land-cover class	Surrounded by:	Convert to:	In Square(s):
Arable bare	Arable barley	Arable barley	Ar (98)
Arable bare	Arable set-aside	Arable set-aside	Ar (98)
Arable bare	Built surface	Built surface	Ar /Pa (99)
Arable barley	Arable harvested	Arable harvested	Ar (98)
Arable barley	Arable set-aside	Arable set-aside	Ar (98)
Arable barley	Grassland - improved	Grassland – improved	Ar /Pa (99)
Arable harvested	Arable wheat	Arable wheat	Ar (98)
Arable harvested	Built surface	Built surface	Ar /Pa (99)
Arable maize	Built surface	Built surface	Ar /Pa (99)
Arable peas	Arable bare	Arable bare	Ar (98)
Arable peas	Arable harvested	Arable harvested	Ar (98)
Arable peas	Arable wheat	Arable wheat	Ar (98)
Arable rape	Grassland - improved	Grassland – improved	Ar /Pa (99)
Arable turnips	Arable barley	Arable barley	Ar (98)
Arable wheat	Arable harvested	Arable harvested	Ar (98)
Arable wheat	Arable rape	Arable rape	Ar /Pa (99)
Grassland – improved	Arable peas	Arable peas	Ar (98)
Grassland – improved	Arable set-aside	Arable set-aside	Ar (98)
Grassland – improved	Arable rape	Arable rape	Ar /Pa (99)
Grassland – improved	Arable maize	Arable maize	Ar /Pa (99)
Grassland – improved	Grassland – neutral	Grassland – neutral	Ar /Pa (99)
Grassland – improved	Grassland - acid	Grassland – acid	Ma (99)
Grassland – neutral	Grassland – improved	Grassland – improved	Ar /Pa (99)
Grassland - acid	Grassland - improved	Grassland – improved	Ma (99)
Fen, marsh, swamp	Grassland – acid	Grassland – acid	Ma (99)
Fen, marsh, swamp	Grassland - improved	Grassland – improved	Ma (99)
Deciduous hedge	Arable harvested	Arable harvested	Ar (98)
Deciduous hedge	Arable peas	Arable peas	Ar (98)
Deciduous hedge	Arable set-aside	Arable set-aside	Ar (98)
Built surface	Arable set-aside	Arable set-aside	Ar (98)
Built surface	Grassland – improved	Grassland – improved	Ar (98)
Built surface	Grassland	Arable bare	Ar /Pa (99), Ma (99)
Built surface	Arable	Arable bare	Ar /Pa (99), Ma (99)
Shadow	Deciduous woodland	Deciduous woodland	Ar (98), Ar /Pa (99)
Shadow	Arable wheat	Arable wheat	Ar /Pa (99)

Table 11. Contextual knowledge-based correction rules as applied to the Arable, Pastural and Marginal trial squares.

Ar (98) = Arable trial square in 1998 CASI data, Ar /Pa (99) = Arable and Pastural trial squares (1999 CASI data), Ma (99) = Marginal trial square (1999 CASI data).

4.2 Phase-2 KBC procedure

The Phase-1 KBC procedures were applied to the spectrally determined parcels. Additional KBC procedures could be performed on a per-pixel basis and after aggregating all contiguous parcels of the same land-cover class. At the aggregate level, a repeat of the above contextual KBC rules enabled additional cleaning to take place. For example, a patch mis-classified as grass in the middle of an arable field, would not have been converted in the Phase-1 KBC procedure if composed of more than one parcel. In addition, at the aggregate level, it was possible to add a suburban label to parcels of grass or woodland land-cover within an urban setting, thereby placing them into BH 17 (Built up areas and gardens).

At the pixel level, a more spatially detailed knowledge-based conversion was performed to correct deciduous woodland / hedge classification and to remove shadow. Per-pixel KBC was particularly useful for correcting between deciduous woodland / hedge and other classes, since the height data was averaged across spectrally defined parcels in the Phase-1 KBC. The greater spatial detail of per-pixel KBC also enabled the attempted conversion of shade parcels into the likely underlying land-cover types, according to a series of decision rules based on context and class priorities.

Although not used in the above KBC procedures, there is no reason why the elevation, slope and aspect information derived from the ALTM data could not be used to identify parcels assigned to classes outside their natural context. This may prove particularly useful in the Upland Landscape type, for which no KBC rules have yet been developed. The issue of texture variations in the height and elevation data as a means of identifying different land-cover types (especially coniferous and deciduous woodland) was not addressed due to time constraints, but could represent a further stage in KBC.

4.3 Additional KBC applied to Arable trial square in 1998 CASI data

Additional KBC procedures were developed for the classified 1998 CASI data of the Arable trial square which sought to recognising features as objects. The temporary conversion of the classified vector data back to a 1m raster grid removed boundaries between adjacent parcels of the same land-cover class and enabled per-pixel filtering operations to be performed on the woody vegetation class. The component features of this land-cover class were identified in a three stage process. Stage 1 involved first shrinking a mask of the woody vegetation class to a point that removed all scattered trees and linear features, and then re-growing the mask remnants guided by a height threshold. This identified patches of woodland and scrub from scattered trees, hedgerows and treelines. Within these latter woody vegetation types, trees could be discriminated from hedges by a greater width and height. Stage 2 involved calculating a focal sum for the remaining woody vegetation mask and applying thresholds to the sum and relative height data to identify the approximate centroids of trees. These were then buffered outwards within the area covered by the woody vegetation class. Re-vectorising these data (Stage 3) enabled the separation of trees in hedgerows or treelines from scattered individuals or clumps according to the surrounding context. A brief KBC to tidy up any ‘stray’ parcels of woody vegetation not captured by the region-growing filters gave the final arrangement of parcels. The final product consisted of a vector database in which the parcels closely relate to ‘real world’ objects (such as the cropped areas of fields, field margins, woodland patches, hedgerows etc). Fourteen land-cover types were identified, including 5 different crop types, improved grassland, neutral grassland, bare ground, built surfaces, water bodies, woodland patches, scattered trees, and hedgerows / treelines (with the presence of trees identified). At this 14 class level, the correspondence with field survey was 88%. Each parcel contained 3-dimensional data relating to the form and terrain context of the object identified.

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APPENDIX V - APPLICATION OF THE PROCESSING FLOW-LINE TO THE CHECK SQUARES

The processes of creating a DSM from the ALTM first pulse data, and CASI flight-line normalisation involved running a series of automated software applications. The methods developed for the trial squares could thus be applied directly and objectively to the check squares. The extraction of 'terrain' from the DSM and the segmentation of the CASI images were both multi-stage processes involving the running of programs which required operator input of threshold values. Optimal values were derived for the trial squares, and these were found to be directly applicable to the check squares. Cleaning the height data to remove the slight edge-of-flight-line errors and registering the CASI flight-lines to the corresponding DSM were manual processes requiring considerable operator interaction. The techniques were readily transferable from the trial to the check squares, but the cleaning and registering processes were unique to each flight-line and so there was no 'correction algorithm' that could be transferred from one image file to another. Recent developments in the Environment Agency image acquisition system should reduce data quality problems, and therefore reduce these highly interactive pre-processing phases from any repeat exercise.

To investigate the transfer of training data from trial to check squares, it was necessary to normalise the spectral data of each check square to match its corresponding trial square. This was achieved by shifting the mean radiance value in each waveband of the check squares to match those of the trial squares. Since an inherent assumption in this procedure was that the type and proportions of land-cover were similar between sites, the transferability of spectral characteristics between sites was restricted. In the Arable and Pastural sites (which have a mixture of grassland and agricultural land-cover types), it was possible to normalise the check squares to the trial squares. This created a set of four 1 km^2 images in which classification was achieved by training the two trial squares and applying these training data to the check squares. Although intended as a 'blind test' the training data were applied to the check squares with minor modifications, inserting three additional land-cover types not present in the trial squares (arable field beans, arable lucerne, and calcareous grassland). The land-cover of the Marginal sites was too distinct to allow their normalisation with the Arable and Pastural sites, but it was possible to normalise the check square to the trial square. This enabled the roll-over of the classification training data from the trial to the check square. However, as the check square contained fewer land-cover types than the trial square, the superfluous training data were not included in the classification. For the Upland sites, the land-cover of the check square was very different to that of the trial square. As a result, these images were not normalised and no attempt was made to transfer training data from the trial square to the check square. Instead the check square was trained independently using known examples of land-cover type (including bracken, bog, fen / marsh / swamp, acid grassland, bare rock).

The KBC rules were also applied directly to the check squares, with only minor alterations required. This involved: slight changes to the height thresholds used for correcting woodland / hedge classification; the addition of extra rules to address problems of water mis-classification in the Arable and Pastural check squares; and the removal of rules relating to classes not present in the Marginal check square. As with the trial square, no KBC rules were applied to the Upland site, since there were insufficient ground data to identify mis-classification. Because the Upland squares were trained for classification independently, there was no need for correction rules to remove incorrectly identified land-cover classes from rolled-over training data. However, if this classification process was repeated over a larger area, the elevation, slope and aspect data supplied by LIDAR would almost certainly be of use in KBC rules.

APPENDIX VI - ISSUES IN THE COMPARISON OF CLASSIFIED AIRBORNE MAGERY WITH FIELD SURVEY DATA

Field survey data were supplied in both paper format (photocopied Field Assessment Booklets) and digital format (a vector GIS in which labels were attached to both the parcels and linework). Correspondence was investigated between the classified airborne data and the digitised field survey widespread Broad Habitat data. Although both data-sets have land-cover data in more detailed classes than the Broad Habitats, this is the only level at which automated validation can be performed readily.

Three potential methods of calculating correspondence were investigated:

1. per-pixel correspondence between the two data-sets at 1 m spatial resolution;
2. labelling the segmented CASI parcels with field survey data and comparing the result with the classified airborne data; and
3. labelling the field survey parcels with the dominant class from the airborne data and comparing the result with the field survey data.

Investigations, as part of the LCM2000 validation work, have shown that rasterising the CS2000 vector data to a 1 m grid alters the spatial area estimates of Broad Habitat classes by an average of just 0.1%. Comparison between the two 1 m spatial resolution grids thus gives a direct correspondence per-pixel between the field survey and airborne image classifications. Attaching the classification of one data-set into the vector boundaries of the other for validation purposes was tested for the Arable trial square in 1998 CASI data. The level of correspondence increased from 86% for method 1, to 88% for method 2, and to 94% for method 3. As these figures suggest, labelling the segmented CASI parcels with field survey data made few changes to the distribution of land-cover as mapped by the field survey. However, labelling the field survey parcels with the dominant class from the airborne data had the effect of generalising land-cover mapped in the airborne data, since the field survey vector had fewer land parcels. As one of the per-parcel approaches made little difference to the per-pixel scores, and the other gave higher scores by generalising detail in the airborne data classification, it was considered best to use a per-pixel approach for calculating correspondence.

Subtle differences exist between the field survey Broad Habitat data and the classified airborne data:

- a one year time difference exists between the 1998 field survey and 1999 airborne imagery;
- a mis-alignment occurs between the two data-sets as the field survey linework, digitised from OS mapsheets, does not meet the 15 cm x-, y-accuracy of the ALTM data (which, here, is considered the baseline for inter-comparisons);
- a distinction occurs between land-use mapped in the field survey and land-cover mapped in the airborne imagery (e.g. BH 3 (Boundary and linear features) is an amalgamation of hedges, roads and railways);
- the field survey does not identify hedges as features having an area, but as boundary features in a separate layer of the GIS database.

To make the two data-sets more comparable, a degree of editing of the field survey data was necessary. The 1999 field reconnaissance data were used, where necessary, to update the land-cover of fields identified as arable or improved grassland in the 1998 field survey data of farmed Landscapes. An object-based classification would have been necessary to achieve the operational identification of BH 3 (Boundary and linear features) in the airborne digital data. Instead, BH 3 is identified in its constituent elements of hedgerows / treelines, walls and built surfaces. To render the CS2000 field data comparable all boundaries identified in the vector linework as hedges or walls were given a nominal width comparable to the airborne data spatial resolution. The inserted hedges were assigned to BH 1 (Broadleaved, mixed and yew woodland), and dry stone walls to Broad Habitat 17 (Built up areas and gardens). Improved registration of the two data sets was necessary since the boundaries in the field survey data were not located with the same geometric precision as with the airborne digital data. The effect of boundary shifting and hedge insertion was to reduce the width of BH 3 (Boundary and linear features) in the field survey digital data and restrict this class to its built surface component. In the correspondence analysis this was regarded along with BH 17 (Built up areas and gardens) as a predominantly built surface. Individual trees that were identified in the field survey were inserted into the vector data-base as BH 1 (Broadleaved, mixed and yew woodland). Finally, BH 13 (standing open water and canals) and BH 14 (rivers and streams) were treated as one water class.

APPENDIX VII – PERCENTAGE COVER ESTIMATES FROM CLASSIFIED AIRBORNE DATA AND FIELD SURVEY

The tables below show percentage cover estimates for 1 km CS squares, calculated from the classified airborne data (1999 CASI and ALTM) and edited field survey data. Edits to the field survey include: the insertion of hedges and treelines as features with width (placed in BH 1); the shifting of boundaries for a better alignment between the two data sets; the placement of the road and railway component of BH 3 into BH 17.

	Airborne data	Field survey
BH 1	22.2%	17.7%
BH 4	60.3%	62.4%
BH 5	13.7%	14.8%
BH 6	0.7%	1.4%
BH 13	0.1%	0.1%
BH 17	3.0%	2.7%

Arable trial square.

	Airborne data	Field survey
UNCLASSIFIED	-	7.2%
BH 1	18.9%	8.7%
BH 2	-	0.8%
BH 4	36.2%	23.9%
BH 5	36.5%	55.0%
BH 6	3.0%	-
BH 14	0.9%	1.7%
BH 17	4.5%	2.7%

Arable check square.

	Airborne data	Field survey
UNCLASSIFIED	-	0.3%
BH 1	10.8%	7.0%
BH 4	20.3%	19.7%
BH 5	59.8%	61.7%
BH 6	0.3%	0.2%
BH 17	8.8%	11.1%

Pastural trial square.

	Airborne data	Field survey
UNCLASSIFIED	-	0.8%
BH 1	13.2%	7.8%
BH 4	16.3%	12.0%
BH 5	65.4%	69.7%
BH 6	0.1%	3.7%
BH 7	0.1%	0.2%
BH 8	-	0.3%
BH 17	4.9%	5.5%

Pastural check square.

	Airborne data	Field survey
UNCLASSIFIED	-	0.2%
BH 1	5.0%	4.4%
BH 4	22.9%	23.1%
BH 5	45.5%	48.8%
BH 6	5.1%	3.7%
BH 8	8.2%	6.3%
BH 11	9.5%	5.9%
BH 13	0.8%	0.0%
BH 17	3.1%	3.9%
BH 8 + 10 mosaic	-	3.5%

Marginal trial square.

	Airborne data	Field survey
UNCLASSIFIED	-	0.2%
BH 1	2.6%	2.0%
BH 4	19.8%	13.4%
BH 5	48.7%	70.7%
BH 6	22.4%	5.7%
BH 17	6.5%	5.2%

Marginal check square.

	Airborne data	Field survey
BH 8	18.4%	7.3%
BH 10	17.5%	5.5%
BH 12	64.1%	48.0%
BH 8 + 10 mosaic	-	1.6%
BH 10 & 12 mosaic	-	37.1%

Upland trial square.

	Airborne data	Field survey
BH 8	23.0%	25.9%
BH 9	0.6%	1.0%
BH 11	4.8%	7.2%
BH 12	69.5%	64.9%
BH 26	2.1%	1.0%

Upland check square.

APPENDIX VIII – COMPARISON OF CLASSIFIED AIRBORNE DATA, LCM2000 AND FIELD SURVEY

The tables below show percentage cover estimates for 1 km CS squares, calculated from the Land Cover Map 2000, classified airborne data, and field survey data. All data sets have a 25 metre spatial resolution (i.e. the airborne and field data have been re-sampled). No edits have been made to the field survey data.

	LCM 2000	Airborne data	Field survey
BH 1	16.25%	20.69%	13.38%
BH 2	-	-	0.06%
BH 3	-	-	2.75%
BH 4	51.31%	62.94%	65.0%
BH 5	18.31%	13.89%	16.44%
BH 6	-	0.69%	1.50%
BH 7	3.69%	-	-
BH 13	-	-	0.06%
BH 17	4.50%	1.81%	0.81%
BH 26	2.50%	-	-

Arable trial square.

	LCM 2000	Airborne data	Field survey
UNCLASSIFIED	-	-	7.13%
BH 1	16.75%	19.38%	7.00%
BH 2	1.81%	-	0.75%
BH 3	-	-	2.56%
BH 4	26.88%	37.75%	32.88%
BH 5	50.50%	37.00%	47.38%
BH 6	-	2.38%	-
BH 13	-	-	-
BH 14	-	0.44%	1.56%
BH 17	4.06%	3.06%	0.75%

Arable check square.

	LCM 2000	Airborne data	Field survey
UNCLASSIFIED	-	-	0.38%
BH 1	3.56%	7.19%	1.50%
BH 2	0.38%	-	-
BH 3	-	-	2.69%
BH 4	53.25%	20.38%	20.69%
BH 5	28.88%	63.88%	64.25%
BH 6	-	0.13%	0.31%
BH 7	6.00%	-	-
BH 17	7.94%	8.44%	10.19%

Pastural trial square.

	LCM 2000	Airborne data	Field survey
UNCLASSIFIED	-	-	0.44%
BH 1	14.19%	10.50%	3.44%
BH 2	1.19%	-	-
BH 3	-	-	3.62%
BH 4	4.50%	15.94%	12.19%
BH 5	72.00%	69.50%	73.31%
BH 6	-	-	4.19%
BH 7	1.44%	0.13%	0.25%
BH 8	-	-	0.31%
BH 17	6.69%	3.94%	2.25%

Pastural check square.

	LCM 2000	Airborne data	Field survey
UNCLASSIFIED	-	-	3.75%
BH 1	3.13%	3.94%	1.81%
BH 3	-	-	4.69%
BH 4	17.94%	23.56%	23.94%
BH 5	37.50%	47.19%	49.00%
BH 6	41.44%	4.25%	4.25%
BH 8	-	7.63%	6.63%
BH 11	-	9.75%	5.94%
BH 13	-	0.75%	-
BH 17	-	2.94%	-

Marginal trial square.

	LCM 2000	Airborne data	Field survey
BH 1	0.88%	2.13%	2.25%
BH 2	0.13%	-	0.06%
BH 3	-	-	5.00%
BH 4	-	17.88%	13.63%
BH 5	82.75%	51.69%	72.38%
BH 6	-	22.94%	6.00%
BH 7	13.38%	-	-
BH 10	2.88%	-	-
BH 13	-	-	0.06%
BH 17	-	5.37%	0.63%

Marginal check square.

	LCM 2000	Airborne data	Field survey
BH 8	-	17.00%	7.56%
BH 10	-	14.25%	5.44%
BH 12	99.88%	68.75%	47.81%
BH 26	0.13%	-	-
BH 8 + 10 mosaic	-	-	1.69%
BH 10 + 12 mosaic	-	-	37.50%

Upland trial square.

	LCM 2000	Airborne data	Field survey
BH 8	79.37%	21.44%	26.63%
BH 9	-	0.69%	0.88%
BH 10	-	-	-
BH 11	-	2.94%	6.81%
BH 12	20.63%	73.50%	64.69%
BH 26	-	1.44%	1.00%

Upland check square.