AVHRR-Based Forest Probability Mapping and Reference Data Collection Method

Tuomas Häme Kaj Anddersson Yrjö Rauste Seppo Väätäinen Anssi Lohi

VTT Automation, Finland
Pauline Stenberg
Helsinki University, Finland
Janne Sarkeala & Paula Susila
Stora Enso Forest Consulting Oy Ltd
Kuparintie 47, FIN – 55100 Imatra, Finland
Tel: +358 40 7497749, Fax: +358 2046 24960
E-mail: paula.susila@storaenso.com
Pamela Kennedy and Sten Folving
Joint Research Centre, Space Applications Institute, Italy

ABSTRACT This paper presents forest mapping method that is based on utilization of AVHRR instrument onboard NOAA satellites. It also presents an airborne method to make collection of ground reference data more effective.

The increasingly weighty requirements for sustainable management of the ecosystems call for improved forest monitoring capabilities. There is an increasing demand for reliable and standardised information on the forests, in the form of statistics, geo-referenced databases and maps. The aim of the AVHRR-based forest probability -project was to produce a calibrated digital forest / non-forest probability database for the pan-European area using NOAA AVHRR satellite data and ground reference data. Mosaic of 49 AVHRR images of the NOAA 14 satellite was used together with CORINE Land Cover classification as ground reference data.

Results showed that “non-forest” areas (e.g., 0-10% forest cover) can be distinguished from areas with medium to high forest cover, but that within all the spectral classes (clusters) representing forests, there was large variation in the forest cover estimated from ground truth data. This variation implies that, because accurate pixel by pixel estimation of forest percentage cannot be expected, the present approach based on probabilities (weighted averages) is better suited for the estimation of forest area cover than the traditional binary classification method.

The forest area at the highest latitudes was somewhat over-estimated whereas the forest area in the Mediterranean and southern temperate zone was slightly under-estimated. This may partly be a reflection of the forest mapping in CORINE. In future work, the best outcome seems to be possible to reach when the resources are concentrated on the improvement of the coverage and quality of the ground data.

Use of aerial digital imagery is a promising way to improve the quality and extent of the reference data for satellite image interpretation. Digital systems challenge traditional film photography due their capability to provide near real-time colour imagery using equipment that can be easily installed to small aircraft. A method called EnsoMOSAIC has been developed to rectify single images into a geo-referenced mosaic in a given coordinate system. Being fully digital and geo-referenced the image mosaic can be integrated into any geographic information system (GIS) and it can also complement traditional forest inventory and satellite images as one GIS data layer.

KEYWORDS AVHRR, forest mapping, digital aerial imagery

1.Objective

The objective of the forest probability mapping project was to produce a calibrated digital forest probability database for the pan-European area using NOAA AVHRR satellite data and ground reference data. The forest probability was defined to be an estimate of the forested area under a pixel of a satellite image. The CORINE land used classification from the area of twelve countries of the European Union and some Central and east European countries represented the ground reference data.

The specific tasks, following from the principal objective, were:

1.To develop a robust and repeatable method for forest / non forest discrimination using AVHRR data so that every pixel has an individual probability for being forest;

2.Provide the forest probability database, *i.e.* the digital forest probability maps;

3.Statistically assess the validity of the probability data.

The work reported in this paper was carried out under contract from the Space Applications Institute of the Joint Research Centre, Ispra Italy. The contract was launched in June 1998 and completed in March 1999. The lead contractor was VTT Automation, Finland, in association with Stora Enso Forest Consulting, Finland and the University of Helsinki.

2.Materials

Mosaic of 49 AVHRR images of the NOAA 14 satellite was used together with CORINE Land Cover classification as ground reference data.

- ***Satellite Data***

Images used in the mosaic were from late July or August 1996. It was assumed that forest vegetation is in as stable development phase as possible during late summer. The red and near infrared channels of the AVHRR instrument of the NOAA 14 satellite were chosen as the input spectral data in the interpretation. The thermal channels were considered to be too weather-dependent for the selected approach, which based on using of calibrated image mosaics. Thermal data were however utilized in cloud masking.

- ***Ground Reference Data***

The ground reference data were from the CORINE Land Cover classification. CORINE (Coordination of Information on the Environment) programme was started in 1985 to facilitate the planning and execution of the European Union's environmental policies. CORINE Land Cover is a geographical database describing vegetation and land use.

3.Methodology

A chain was developed to produce reflectance mosaics. A forest probability map was computed over the computed mosaic.

3.1. pre-Processing

Image pre-processing consisted of the following tasks:

1.image extraction from the distribution media (HRPT, SHARP-1 and NOAA LAC);
2.computing or extracting the tie point grid with sun and satellite angles;
3.radiometric corrections;
4.cloud masking;
5.geometrical corrections for individual images.

- ***Radiometric Corrections***

Raw digital counts were first converted to TOA (Top Of Atmosphere) reflectance using time dependent calibration coefficients that are published monthly by NOAA. Then these reflectance values were converted to atmospheric-ally corrected top-of-canopy reflectance by using the SMAC (Simplified Method for Atmospheric Correction) algorithm, (Rahman et al. 1994).

The aerosol optical depth of the atmosphere was found to be the most significant variable affecting this algorithm. Several images were computed using different aerosol depth values and then their reflectance values over mature coniferous forests were studied. The value 0.1 produced similar reflectance values that could be found in literature, 1.5% on the red channel and 15% on the NIR channel.

Finally a BRDF (Bi-directional Reflection Distribution Function) correction was applied. As a result, the images were normalized to a nadir view with a solar zenith of 45°. The BRDF method was based on the Roujean model with forest surface parameters presented by (Wu et al. 1995). The atmospheric correction was applied for every pixel on the image.

- ***Cloud Masking***

A threshold for red and thermal channels was defined interactively to mask the clouds out. A pixel was masked if the intensity on red channel was higher than the reflectance limit *and* the intensity on thermal channel 4 was lower than the temperature limit. Cloud shadows were masked from the rectified images by removing 5 pixels (≅ 3 km) north from a detected cloud.

- ***Geo-Coding***

In image geo-coding a tie point grid was used. For image re-mapping, a coordinate transformation function was computed at every pixel of the output image by using three closest geo-referenced points on the grid and their respective image coordinates. So, using piecewise linear mapping functions the rectification process was carried out throughout the whole image.

Image geo-coding consisted of the following steps:

1.A reference image mosaic covering the whole area of interest was compiled using 8 AVHRR scenes. Ground control points were measured manually using images and different maps.
2.Computed or extracted tie point grids were used to approximately rectify all 49 images.
3.Control points were generated automatically using a software that uses sub-image correlation between windows of two images (Andersson 1998).
4.The original tie-point grid was corrected using the accurate geographical information that was derived from the measured ground control points.
5.All radiometrically corrected images were rectified again to a latitude–longitude coordinate system. The pixze was set to 0.006 degreesel sinorth and 0.01 degrees east. This was equivalent to about 700 meters in north direction and 400–1000 meters in east direction, depending on the latitude.

- ***Mosaicing***

The final mosaic was compiled from radiometrically and geometrically corrected images. The compilation itself was a simple image patching task, since all the images were in the same latitude-longitude projection. Clouds and cloud shadows had been masked earlier from individual images and in cases of overlapping images the mean value was used.

The mosaic compilation seemed to work well. No geometrical shifts between images could be seen. Also the radiometric corrections seemed to have been successful since no intensity limits were visible between the images. Still some blank areas remained, due to clouds, especially in the mountainous areas.

3.2. Image Interpretation

The image interpretation algorithm has the reflectance mosaic as input, and produces a value of the target variable 'forest probability' (FP) for each pixel of the study area. The method used both unsupervised and supervised classifications as tools but the final result is a continuous variable on forest probability (estimate on forest area under the pixel). The interpretation chain had four major steps starting from the existing image mosaic:

1) Clustering

Image clustering was done using an unsupervised clustering method (Häme et al. 1998). In the method, an automatically selected training sample consisting of 2 by 2 pixels representing homogeneous ground targets is clustered in a predetermined number (N) of clusters, using the k-means algorithm. The criterion for the homogeneity was the standard deviation vector of the reflectance values of the 2 by 2 pixel group compared to the standard deviation of the whole image.

Clustering was performed on the whole area, and also separately for the Mediterranean and non-Mediterranean regions (pre-clustering stratification). In all cases the number of clusters was set to N=50, which was found to give a good coverage of the "spectral space" defined by the red and NIR reflectance values over the study area. In case when pre-clustering stratification had not been done, post-clustering geographical stratification was implemented by computing the value of FP for a cluster separately for the different regions. The best approach was selected to produce the final forestry map. A hypothesis was taken that if there were no clear differences between the non-stratified and stratified approach, the non-stratified approach would be selected.

The pixels representing water were masked out in the clustering. If a pixel had 12.0 percent or a lower near-infrared reflectance it was assigned as water. This threshold was defined interactively.

2) Cluster Statistics and Selection of Observati-ons forG round Sampling

The mean spectral vector (m_c) and the covariance matrix (S_c) between the two spectral channels was computed for each cluster (c) using the spectral intensity vectors (x) of the cluster members, and a two-dimensional normal density function (f_c) was estimated based on these statistics:

$$f_c(x) = \frac{1}{2\pi |S_c|^{1/2}} e^{-1/2(x-m_c)^T S_c^{-1}(x-m_c)}$$

Equation 1

The quadratic product appearing in the exponential of Equation 1 represents the squared distance from a spectral vector (x) to the class mean (m_c) as scaled and corrected for the variance and covariance of the class (Strahler 1980). Under the normality assumption, it is $\chi 2$–distributed with two (the number of channels) degrees of freedom. The condition:

$$(x - m_c)^T S_c^{-1}(x - m_c) < \chi^2_{1-\alpha}$$

Equation 2

rejects observations, for which the probability of belonging to class (c) is smaller than α.

A threshold value of 3.219 (α=0.2) was used. This meant that observations (x), for which the quadratic product (Equation2) exceeded this value (forall classes (c)) were not selected as representatives for the ground sampling. The chosen threshold cut out 20 percent of the observations selected by the clustering (the training data). By confining the ground sampling to the central part of a cluster, the influence of members in border or overlapping areas on the class content is reduced.

3) Determination of Class Contents

For each sample unit (j) of a given class (c), the forest probability $FP_C(j)$ was estimated as the area proportion of the unit classified as forest in the CORINE data. The final value of the target variable FP_C for each class was computed as the mean of the values obtained for its sample units (j). If pre-clustering stratification had not been done, the value of FP_C was calculated separately for the Mediterranean and non-Mediterranean regions (post-clustering stratification).

The sampling unit applied for CORINE was 1 km by 1 km. It was assumed that this size of unit fits within the 2 by 2 pixel unit of the clustering even if some rectification errors were involved.

The input data for the ground sampling with CORINE were the coordinates of the square-form sample units and their respective cluster identification. The 1 km^2 squares were used to cut the CORINE land use. The area by the CORINE land use class was calculated within each square. Then the areas were summed up into two classes: forest and non-forest, which were converted into the forest coverage (%). The forest classes as CORINE codes were: broad-leaved forest (311), coniferous forest (312), and mixed forest (313).

The output of the sampling phase was the forest coverage mean and its standard deviation for each AVHRR cluster. The forest coverage mean values were in a later phase used as input to compute the final forest probabilities.

4) Computation of Forest Probability

In the final stage, a value of FP was assigned to each pixel on the study area. It was computed as the sum of the product of class membership probabilities for the pixel and the class content. The probability P(c|x) of a pixel with spectral vector (x) to belong to a specific class (c) was set proportional to the value of the density function of this class at x, $f_c(x)$ (Equation 1), i.e., equal *a priori* class probabilities were assumed (Gorte & Stein 1998). In computing class membership probabilities for each pixel, the probabilities P(c|x) were scaled so that the sum over all the classes equalled 1.

The forest probability FP(x) assigned to the pixel (x) was obtained by multiplying the class membership probabilities P(c|x) by the class values (FP_C), and summing over all the classes:

$$FP(x) = \sum_{c=1}^{N} P(c|x) FP_c$$

Equation 3

Three unsupervised classifications were done: 1) classification of the whole mosaic; 2) classification of the Mediterranean part of the mosaic; 3) Classification of the mosaic excluding the Mediterranean part. The CORINE sampling was performed accordingly. In addition, the CORINE sampling was also done in a stratified manner from the classification of the whole mosaic. FIRS European forest regionalization and stratification vector data and the final forest probability raster map were converted into the same coordinate system with the CORINE data (Lambert azimuthal projection).

The Mediterranean and the Temperate and Boreal classifications were combined so that the forest coverage percentages by FIRS strata were computed from the relevant classification. There were 19 regions and 119 strata on land and within Europe. In the AVHRR output, water and cloudy areas had a specific code. These areas were neglected in the computation. The forest percentage for a FIRS region or stratum was computed using pixels for which the probability value had been possible to compute.

The FIRS strata and AVHRR map geometry matched generally well. In the eastern part of the study area there were displacements of some kilometres.

4.Results

4.1. Clustering Results

- ***General***

A key clustering parameter gave the highest allowed standard deviation (length of the deviation vector) within a candidate object (2 by 2 pixel group) compared to the standard deviation of the whole image (Häme et al. 1998). This parameter controls the size of the sample in the clustering process. A lower value had to be given in the clustering of the whole mosaic because the area was large and thus the number of candidate samples higher (Table 1). The CORINE data were not available in the vast majority of the target area. This is shown as a relatively low CORINE sample size in the classification of the whole image.

Table 1. Statistics of the three clustering classifications. Numbers in the parenthesis show the sample size in the post-clustering stratification.

Clustering characteristics (Whole area)						Size of CORINE sample
No. Of clusters	St. Dev. Limit, %	No. Of Obs. In clust.	Prop. of whole image, %	No. of obs. In largest cluster	No. of obs. in smallest cluster	
50	2.0	608048	2.2	53944	77	39637 (28865N) (10744M)

Clustering characteristics (Mediterranean area)						Size of CORINE sample
No. of clusters	St. Dev. Limit, %	No. Of Obs. In clust.	Prop. of whole image, %	No. of obs. In largest cluster	No. of obs. in smallest cluster	
50	6.0	137968	9.9	4725	572	99455

Clustering characteristics (Temperate & Boreal area)						Size of
No. of clusters	St. Dev. Limit, %	No. Of Obs. In clust.	Prop. of whole image, %	No. of obs. In largest cluster	No. of obs. in smallest cluster	CORINE sample
50	4.0	366926	2.9	22458	36	48968

Those 2 by 2 pixel groups that passed the deviation test and were thus included in the clustering process were not evenly distributed in the land cover classes but concentrated on the forestry classes. This is because the forests, with their low reflectance values, showed higher spatial homogeneity.

This was not assumed to harm the result, because the number of observations within a cluster was rather high anyway. However, there is a low risk that ground cover types that are naturally somewhat heterogeneous, like urban areas, were not represented in the clustering process at all.

- ***Properties of the Clusters***

Figures 1, 2 and 3 show that the ten-percent forest border in the spectral space runs consistently between red reflectance 5 to 10 percent so that if the red reflectance is close to 10 percent, the near infrared reflectance is low.

The cluster number 50 seems to be quite adequate in the clustering of the whole image. In the stratified approach, particularly in the Temperate and Boreal area, already a lower cluster number would likely have been high enough.

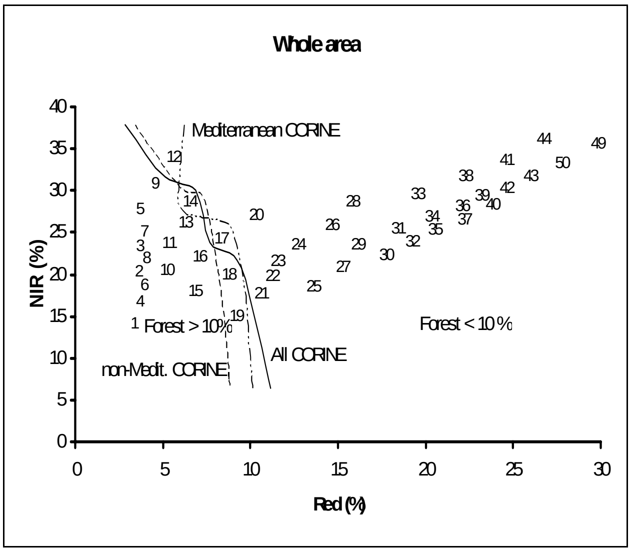

Figure 1. Spectral mean values of the original clusters in the clustering to the whole mosaic. The drawn lines divide the spectral space to clusters whose forest percentage is above and below 10 percent according to the CORINE sample. Solid line: All the CORINE data has been used in the sampling; Dash and dot line: only Mediterranean CORINE data has been used in the sampling (post-stratification); Dash line: only the Temperate and Boreal CORINE data has been used in the sampling (poststratification).

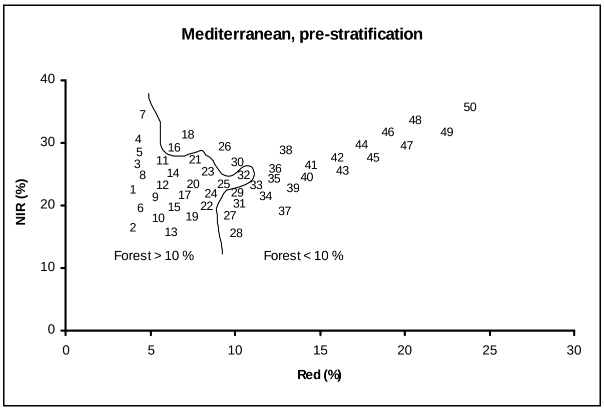

Figure 2. Spectral mean values of the original clusters in the clustering to the Mediterranean mosaic. The line divides the spectral space to clusters whose forest percentage is above and below 10 percent according to the CORINE sample from the Mediterranean zone.

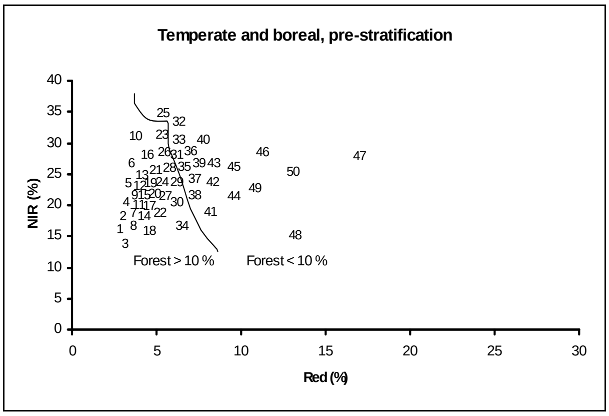

Figure 3. Spectral mean values of the original clusters in the clustering to the Temperate and Boreal mosaic. The line divides the spectral space to clusters whose forest percentage is above and below 10 percent according to the CORINE sample from the Temperate and Boreal area.

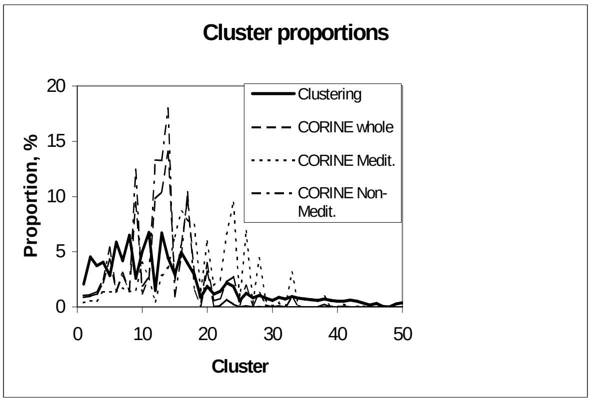

Figure 4. Cluster proportions in the original clustering of the whole area (solid line) and in the CORINE sample (dashed lines).

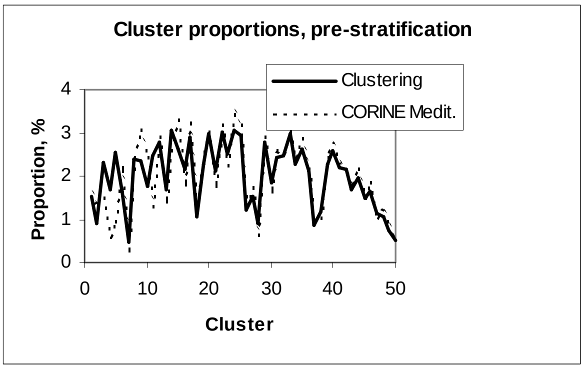

Figure 5. Cluster proportions in the original clustering of the Mediterranean area (solid line) and in the CORINE sample (dashed line).

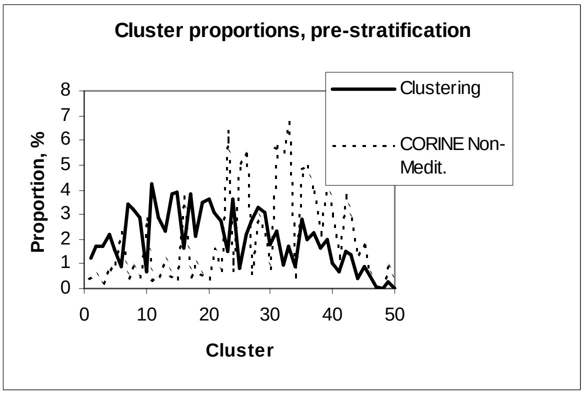

Figure 6. Cluster proportions in the original clustering of the Temperate and Boreal area (solid line) and in the CORINE sample (dashed line).

Figures 4, 5 and 6 indicate that the CORINE data was representative for the Mediterranean zone but not for the Temperate and Boreal area. In the Mediterranean area (pre-clustering stratification) the area proportions of the original clusters match very well with the cluster proportions in the CORINE sample. In the Temperate and Boreal area the CORINE sample was concentrated on the higher cluster numbers, which meant clusters representing lower forest percentage. However, the sample size was in all samples several hundreds for clusters that represented any significant forest proportion.

The standard deviations of forest percentages of each cluster were high. In the forested classes they were typically over 30 percent units. The stratification did not clearly decrease the deviation with one exception. When the clustering and CORINE sampling were made to the Temperate and Boreal area only, the standard deviations of the clusters, representing highest forest cover percentage (low cluster numbers), were less than 30 percent, which was lower than in the other sampling / clustering combinations. In this pre-stratification approach, only nine clusters (from 42 to 50) had forest percentage less than ten percent.

When the clustering was done to the whole mosaic and the CORINE sampling to the Temperate and Boreal area only, 35 clusters had forest percentage less than ten percent. This means that the non-forest are as were concentrated in the Mediterranean zone that was included in the clustering but not in the CORINE sample. It also means that the open areas had high reflectance dynamics, which increased the number of clusters in the high reflectance areas.

It was concluded that the best alternative in image interpretation was the stratified approach in which the image interpretation is done separately to the strata. The justification to this conclusion was the good matching of the CORINE and ground data in the Mediterranean area and the decreased standard deviations of the most forested classes in the Temperate and Boreal area. The main reason to the effectiveness of the stratification may have been the poor geographic coverage of the CORINE, particularly the missing boreal zone, rather than improvement of the image interpretation due to stratification. The justification for the pre-clustering approach was not very strong because the spectral forest limit in the Mediterranean and the Temperate and Boreal strata was similar.

Results showed that “non-forest” areas (e.g., 0-10% forest cover) can be distinguished from areas with medium to high forest cover, but that within all the spectral classes (clusters) representing forests, there was large variation in the forest cover estimated from ground truth data. This variation implies that, because accurate pixel by pixel estimation of forest percentage (FP) cannot be expected, the present approach based on probabilities (weighted averages) is better suited for the estimation of forest area cover than the traditional binary classification method.

The computed forest probability database was compared with forest areas from CORINE and with official forest statistics. The comparison showed that the forest percentage of those 12 countries of European Union, which had CORINE data available was underestimated by 2.0 percentage units compared with the aggregated CORINE forest area. Compared to the forestry statistics, the underestimation was 4.4 percentage units.

In the comparison it was assumed that the proportion of forests in the cloudy areas of the image mosaic was the same as the proportion of the forests in the whole country. This is likely a conservative correction of the cloud effect since mountainous areas are often cloudy and also have a high forest percentage. However, the correction may also have incorrectly increased the forest percentage in the Alps because the snow-covered tops could not be discriminated from the clouds. Due to the correction, also the snow-covered areas have increased the forest percentage of a country. The cloud percentage within the 12 EU countries was 4.4. If the cloudy areas had been neglected the underestimation compared to the CORINE data would have been 3.0 percentage units.

Of the larger countries, involved in the comparison, the biggest underestimates in the probability maps were in Portugal (-7.4 percentage units) and France (-5.9 percentage units). Ireland had as high overestimation as 15.4 percentage units. This was because the moor-land was also classified as forest. The second largest overestimation was in Austria, 3.0 percentage units but without the cloud correction the forests would have been underestimated by 2.2. percentage units.

5.Discussion

Clustering that was performed on the whole area without any stratification resulted in fairly large standard deviation in the ground content (FP) within a spectral class and overlap of the range of FP between classes. Apart from the variation caused by the data itself, this confirms earlier observations, that areas with different forest cover can generate similar spectral signals and, conversely, that different signals may correspond to similar forest cover.

The best results were considered to have been achieved using the pre-stratification approach, which meant division of the target area into two geographic regions before the image clustering and consequently also in the ground sampling phase. However, comparison between results obtained using no stratification, and pre- and post-clustering stratification, respectively, showed that the separation between "forest" and "non-forest" using a threshold value of 10 percent worked well with all methods. The decrease in the variation in forest percentage (FP) within classes was approximately similar by the pre- and post-clustering stratification methods. The main difference was that, with pre-clustering stratification, a more representative ground truth sample was obtained for the Mediterranean region, which was under-represented when clusters were formed without stratification. For the Temperate and Boreal region, such comparison cannot be made because the boreal region was missing from the ground truth data.

Although the CORINE mapping has been made at different years in different countries and although the mapping accuracy is not tested using any established procedure, the CORINE seemed to serve as ground reference data rather well. Also the comparison between forest statistics, derived from CORINE, the official forest statistics showed quite a good performance of CORINE.

- ***Suggestions For Method Improvement***

In future work, the best outcome seems to be possible to reach when the resources are concentrated on the improvement of the coverage and quality of the ground data.

Also it could be beneficial to use some ancillary data to discriminate the arctic areas north of the tree line. However,in such an approach the reisa risk that the border of tundra is set to an incorrect location, if the ancillary data are not reliable. At least some obvious errors can be eliminated with the ancillary data.

Despite practically all relevant AVHRR scenes over one summer were checked, significant parts of mountainous and northernmost areas were still cloud-covered. A partial solution is to combine images from different summers. In an earlier study images from three years were successfully combined (Häme *et al.* 1997). Another solution could be to utilize SAR images on cloud covered areas. This could be helpful at the northern areas, which often are flat. In the mountainous regions experiences from the SAR data have not been particularly encouraging.

This study was limited, according to the contract, to forest area estimation. However, the developed method can be used to estimate any variable of which ground data are available.

- ***Digital Aerial Imagery***

In the area of the European Union, the CORINE data was available to serve as ground reference data. However, the CORINE data do not cover yet whole Europe and the existing data are ageing. In most parts of the globe CORINE-type data do not exist. Therefore new tools should be developed for ground reference data collection.

One possibility for ground reference data collection is the use of airborne imagery or new high resolution satellite imagery (e.g. IKONOS). The availability of this new satellite imagery, however, is still unknown. Traditional analogical aerial photographs could be utilised but often the situation is such that new photos are not available. The imaging work is also too expensive for large areas, like is the case in AVHRR-based forest mapping.

Development of computer and camera technology has made low-cost aerial digital imaging systems available. Since the data is directly in digital form, these systems challenge traditional film photography by providing near real-time colour imagery for information systems. One such system is EnsoMOSAIC.

In AVHRR-based mapping in global or continental level the digital aerial imagery could be utilised by imaging sample stripes from chosen ground reference areas. The altitude for the imagery flying should be such that the ground vegetation could be classified at least with the accuracy of CORINE-type classification.

Since the resolution in digital aerial imagery is adjustable (between 0.2 and 5 metres), the imagery could be utilised in two phases. First phase would serve the classification needs and the other, more accurate imagery, could serve in detailed ground truthing. With resolutions better than one meter, the single trees can be detected from the imagery.

Thousands of images are needed to analyse large areas. Processing of large amounts of data is impossible without special computer software. Furthermore, there are usually big radiometric and geometric differences between digital images. In order to create output maps regardless of these problems, an integrated system is used to collect the data and to create continuous image mosaics of tens or hundreds of thousands of hectares. Single-line mosaics with specified line intervals could also be processed and used to obtain quickly ground control points (dependent on terrain and flight conditions).

The specification can be considered as advantages or disadvantages depending on the alternative imagery source. For example, aerial photos have better resolution but they are slower to obtain. New high resolution satellite imagery, on the other hand have about the same specification than a comprehensive view of a large area of interest.

The airborne part of an operational aerial imaging system includes a digital camera (e.g. Minolta or Kodak) and a differential GPS (Global Positioning System) integrated with navigation software. The images are captured on the hard disk with GPS coordinates.

After the imaging flight, the images are processed on standard PCs into large geo-referenced mosaics. The rectification is based on bundle block adjustment (BBA). The approach considerably differs from the registering of raw satellite data into map coordinates: in the image rectification there is no need for ground control points. If accurate GPS data have been registered during the flight, it is possible to proceed by using the image frame coordinates only. In order to obtain a result of good radiometric and geometric quality corrections are calculated for aircraft inclination, camera distortion and differences in terrain elevation, sun angle and local radiometric conditions. Digital terrain models are created internally of digital stereo pairs, or entered from external sources, to eliminate elevation differences to produce an orthomosaic.

Being fully digital and geo-referenced the image mosaic can be integrated into any information system and it can also complement traditional inventory and satellite images as one GIS data layer.

The typical specifications of EnsoMOSAIC imagery are:

1)Time needed: during a typical imaging day, some 20000 hectares with one-meter resolution can be covered. Mosaic processing for 20,000 ha takes about one week.

2)Reliable acquisition: the image acquisition can be done from below the clouds and the image quality can be assessed immediately.

3)Geometric resolution: ground resolution is between 0.3 meters and 2 meters (flying altitude 400-3000 m, respectively).

4)Spectral resolution: 3 visible channels with standard (Minolta) camera or green, red and NIR with digital video camera.

5)Geometric accuracy: 1-5 m with ground control points and ortho-rectification, 5-20 m without EnsoMOSAIC imagery. Their difficulty will be very narrow (20 km) imagery strip.

Some other examples of the fields where a digital image mosaic can make a valuable contribution to forestry are:

Operational forestry planning. This high-resolution system is particularly well suited for operational planning, such as road and silvicultural planning.

Monitoring and control of forestry operations. By repeating the flights it is possible to monitor the development of forest resources, e.g. forest plantations, concessions, exact occurrence of forest fires, expansion of forest damage, or success rate of an afforestation programme.

Base and thematic mapping, especially in the tropics where existing maps are often old and inaccurate.

Strategic land-use planning where even a lower resolution (2-5 metres) is detailed enough.

Future development is expected in camera resolution and in development of infra-red channels for digital still cameras, in terrain model applications, and in completely automatic mosaic processing (e.g. Holm 1995). Automatic single tree detection using pattern detection techniques and, as a consequence, automatic stand volume calculation, will also be in practice in the near future.

References

Andersson, K., 1998. NOAA AVHRR Data Processing Software, User's Guide (Ver 2.0). VTT Automation, Interim report.

Gorte, B. & Stein, A. 1998. Bayesian classification and class area estimation of satellite images using stratification. IEEE Transactions on Geoscience and Remote Sensing 36(3):803-812.

Holm, M. 1997. PC-based system for capturing airborne video imagery and creation of digital aerial mosaics. Paper presented at Airborne Remote Sensing Conference, 7-10 July 1997, Copenhagen, Denmark.

Holm, M. 1995. Global object reconstruction using airborne video imagery: the ESPRIT-III GLORE project. Automation Technology Review 1995. VTT Automation. P. 71-79.

Häme, T., Heiler, I. & San-Miguel Ayanz, J. 1998. An unsupervised change detection and recognition system for forestry. International Journal of Remote Sensing 19(6):1079-1099.

Häme, T., Salli, A., Andersson, K. & Lohi, A. 1997. A new methodology for the estimation of biomass of conifer-dominated boreal forest using NOAA AVHRR data. International Journal of Remote Sensing 18(15):3211-3243.

Rahman, H., Dedieu, G., 1994. "SMAC: a simplified method for the atmospheric correction of satellite measurements in the solar spectrum". International Journal of Remote Sensing, Vol 15.

Strahler, A.H. 1980. The use of prior probabilities in maximum likelihood classification of remotely sensed data. Remote Sensing of Environment 10:135-163.

Wu, A., Li, Z., Cihlar, J., 1995, "Effects of land cover type and greenness on AVHRR bidirectional reflectances". Journal of Geophysical Research, Vol 100.