# Conclusion

This thesis investigated the potential of optical remote sensing using cutting-edge data acquisition and processing methods to provide information on temperate forest status at the stand level. Ancillary data were also incorporated in the perspective of proposing an integrated approach that exploits optimally the already available data on forests. We provide in the following sections a summary of its main results, general conclusions and some directions for future research.

## Summary of the main results

Aerial photographs have been widely used in forest mapping by visual interpretation and manual stand delineation. We logically firstly studied the feasibility to automate the interpretation process by digital classification for forest stand discrimination. The proposed method combines digital vector and raster data in a per-parcel classification approach. The classification variables were spectral values in the red, green and blue bands, as well as texture indices derived from the grey level co-occurrence matrix. The discriminant analysis showed that in the context of this study, it was possible to identify nine forest stand types with an accuracy of around 80%. The forest stand types were defined on the basis of the species composition and class height. We must note however that the performance of the method for discriminating the different broadleaf stand types remained weak. On a methodological point of view, we should underline the importance of texture information in 1-m resolution images of forest areas. Among the three variables which had the highest discriminatory power, there were two texture features derived from the GLCM.

The methodology developed on the basis of digital aerial photographs was then extended to very high spatial resolution images acquired by space-borne sensors. Such images from the first commercial satellites, IKONOS and QuickBird, raised a great interest in the scientific community as they constituted a major improvement in the remote sensing field. From the forester point of view, they were also expected to allow producing cartographic data at large scales, comparable to those achieved using the traditional methods based on aerial photographs.

IKONOS images were processed for two purposes: firstly for forest mapping, i.e. dealing with forest type discrimination and geometric accuracy issues; secondly for dendrometric variables retrieval in order to better describe the forest stands.

As far as the forest mapping objective is concerned, it has been shown that the orthorectified IKONOS images comply with the requirements of large scale mapping, up to 1:10 000. This result outperforms the usual foresters needs in positional accuracy of the cartographic products. Furthermore, the geometric correction of the satellite images is more efficient than the orthorectification of aerial photographs.

With regards to forest stand type discrimination, four age classes in coniferous stands and two levels of mixed stand classes were identified along with the classic distinction of coniferous vs. broadleaf stands. The overall classification accuracy was about 83%. Moreover, the main classification errors were related to the discrimination between two adjacent age classes.

The discrimination between broadleaf species was again unsuccessful. For mature forest stands, it is actually possible to discriminate visually three coniferous species: larch, Scots pine and Norway spruce (Kayitakire et al., 2001). But, as there were few stands of larch and Scots pine, they were confused with Norway spruce stands by the automatic classification.

Thanks to high spatial resolution and to the presence of the near-infrared spectral band, it was possible to better characterise the mixed stands (mixture of broadleaf and coniferous species) than using either aerial photographs or satellite images of coarser spatial resolution. The information produced by such a classification complies with forest management requirements for a preliminary scheduling of forest operations.

Dendrometric variable retrieval was carried out on coniferous stand. The estimates based upon GLCM texture features derived from an IKONOS 1-m spatial resolution image were found to be feasible and reliable. Relative prediction errors of two out of the five studied forest variables were within usual sampling inventory errors (top height and stem circumference) while two others (basal area and age) were close enough to the 15% relative error threshold, so that their results might be useful in forest planning. The stem density estimation error remained too high for relevant use.

This part of the research allowed also discussing the influence of GLCM parameters to the forest variables estimates. Their effect can be related, on the one hand, to the forest characteristics and the spatial resolution of the image, and on the other hand, to the sun-target-sensor geometry during the image acquisition. For example, a good estimate of the top height was provided by the *correlation* measure calculated in the direction parallel to the tree shadows. It also appeared that the *correlation* measure performed better than other texture measures because the sun zenith angle was high and the sensor was in a forward position nearly the principal plane, enabling large tree shadows to be captured. The *correlation* also provided the best estimates of the circumference and age which were strongly correlated to top height. On the other hand, stem density and basal area were better estimated by the *contrast* measure computed with the GLCM orientation parameter set to the direction perpendicular to the shadow direction. Further work based on images acquired with a different geometry is however needed to extend this conclusion. It could, therefore, help to better understand the relationship between forest structure and GLCM texture features in very high spatial resolution imagery.

The study demonstrated the large potential of very high spatial resolution imagery for coniferous forest structure retrieval in temperate regions. However, further research is also needed to document the performance of the retrieval in different environmental conditions, including topographical changes, other species and more heterogeneous stands. Nevertheless, the method could be implemented in order to get data on the forest parameters for international reporting and local planning, with better accuracy than the nation-wide sampling inventories. As underlined in the introduction, future forest assessment ordered by FAO will require more detailed data than it was used for the past assessments. If the national inventory system is not up-to-date or does not exist at all, the satellite images constitute a very valuable alternative or complementary data source.

The chapters 2 and 3 focused on the gain due to the enhancement of the spatial resolution. It is indeed the most remarkable factor in remote sensing since its interpretation is straightforward. However, several studies have suggested that enhanced spectral resolution and (near-)simultaneous multiple view-angles should improve the quality of forest stand attributes that are derived from remote sensing data analysis. This was tested thanks to the unique opportunity that was offered by the CHRIS-PROBA system.

The contribution of the multiple view-angle remote sensing data to forest stand characterization has been investigated with emphasis on assessment of the specific contribution of the angular information compared to traditional spectral signature. The six forest types studied here showed different directional signatures (revealed namely by the anisotropy index) but most of them could be discriminated on the basis of the near-nadir spectral signature alone. The means of reflected radiances of this near-nadir image at the red-edge and near-infrared wavelengths were found significantly different for all pairwise comparisons within either coniferous or deciduous stands, except for the comparison between the mature deciduous stands. Their mean radiances were significantly different in the images acquired with a FZA of +36°, i.e. when the sensor was close to the plane perpendicular to the principal plane. It appeared therefore that, on the one hand, the contribution of the multiple view-angle data is important in differentiating some particular forest types in relation to their structural characteristics, and on the other hand, that the spectral effects are the main driving factor in discriminating most forest types. Spectral data from the +36°-FZA image were sufficient to discriminate the six forest types that have been studied. Moreover, the CHRIS images acquired in forward configuration showed more often significant radiance differences between forest stands of the same group –deciduous or coniferous– whereas absolute radiance values were higher in the backward images than in the forward images (figure 4.7 and tables 4.5 and 4.6). With respect to this, the possibility to choose the viewing angle was more important than acquiring images with several angles systematically.

# General conclusions

Remote sensing data have played an important role in documenting the condition of forest stands. Historically, aerial photography was the primary source for characterizing forest stands. They are still extensively used in forest inventory and mapping, usually by photo-interpretation. As digitial data, satellite images and digital or scanned aerial photographs, become common, it is convenient to evaluate their suitability to derive forest information at the stand level by the means of automated image processing.

We showed that forest stand could be automatically classified with high accuracy according to their species composition and height category. The results of the classification of satellite images are expected to be more robust than those obtained with aerial photographs as the former are usually radiometrically well calibrated. The satellite images are also preferred to aerial photographs as they are less subject to parallax and high view-angle deformations and allow more flexibility in their acquisition. High view-angle and parallax-related problems are almost systematically invoked in studies using aerial photographs (StOnge and Cavayas, 1995; Levesque and King, 1999; Solberg, 1999; Hyyppa et al., 2000; Anttila, 2002; Tuominen and Pekkarinen, 2005), and the authors recommend to restrict the analysis to the central part of the photographs. Technological progress in airborne digital camera should allow to get data that are better calibrated and that are corrected for geometric deformations. The VHSR images could therefore be processed whatever the type of platform from which they have been collected, and the approach that we proposed could be applied even in a multi-source data classification. The parcel-based classification allows a readly combination of data from different sources.

With respect to comparison of aerial photographs and VHSR satellite images, there is a controversial debate on the cost effectiveness of the one or the other source. The prices change rapidly as the technologies evolve, but also they depend on negotiations with data providers. For our discussion, we can reasonably assume that the cost difference between these data sources is small so that we can keep comparison on technical matters. Therefore, if we had to choose between aerial photographs and VHSR satellite images, we would recommend the latter.

Moreover, we showed that detailed dendrometric data can be derived from VHSR satellite images with error levels comparable to that of extensive field inventory. The method that we proposed can be efficiently combined with field inventory to obtain a complete coverage of forested areas. The field work will typically provide reference data for model calibration and validation. Together with the forest stand classification, these results have been confronted to forest management requirements. We use the classification of forest information needs that has been proposed by Weintraub and Cihlar (1991). Thus, IKONOS-2 images can be successfully used at the tactical planning stage (preliminary operation scheduling) as they fulfill the requirements in positional accuracy, the minimum mapping unit size and age classes discrimination. At the operational planning stage, they could provide precise forest boundaries and more stand attributes like height, stem diameter, stand density and in some extent, the species composition.

In satellite-based remote sensing, directional effects are usually considered either as noise to remove from data (e.g. in multi-temporal compositing or in topographic normalization) or as valuable source of information on the structural features of the sensed objects (e.g. BRDF modelling or direct incorporation of multiple-view angle data in the analysis as supplementary variables (Kimes et al., 2006)). A third option has been the selection of nadir or near-nadir images to avoid reflectance variations due to changing viewing angle. This option is doubly beneficial as it allows to avoid parallax distortions as well.

However, it can be beneficial to select some acquisition configurations according to the aim of the analysis. This option is rarely exploited today, but it can become usual in the future as the satellite are more and more often provided with the off-nadir pointing capabilities and the choice of satellite images becomes larger. For instance, images acquired in backward and near the hot-spot configuration should be avoided if one is interested in forest stand characterization using texture analysis and VHSR images. More generally, as the proportion of the sensed shadow play an important role in the spectral and textural signatures of forest stands, acquisition configurations falling in the principal plane are less interesting for effective forest stands discrimination and characterisation.

# Directions for future research

All the results reported in this thesis are about forest stand mapping and characterisation. The availability of stand boundaries is a sine qua non condition of such analysis. We derived the stand boundaries from existing databases or from manual digitising. Thus this may be a major limitations if no ancillary data are available and the cost of manual digitising is incompatible with the benefits of using remote sensing techniques. For instance, by comparing per-pixel and per-parcel classifications for crop mapping, De Wit and Clevers (2004) reported that per-parcel classification decreased the effort for classification from 1500 to 500 man-hours, but the effort for creating the crop field database by manual digitising was estimated at 2300 man-hours, which almost doubles the total man-hours spent for mapping the crops using the per-parcel approach. We can expect an increased workload for digitising forest stands as they have more complex shapes. An effective method of automatic stand boundaries extraction will be, therefore, highly beneficial to the utilisation of very high spatial resolution images in operational forestry. We think that this is the most promising direction for future research.

An other important issue in forest remote sensing is the topographic effects. We selected flat terrain for the dendrometric variables retrieval. However, forests are often on hilly terrain, namely in regions with high human population density where forests are intensively managed. A number of methods for topographic effect correction have been proposed (e.g. Richter, 1997, 1998; Shepherd and Dymond, 2003; Svoray and Carmel, 2005), but, as stated by Riano et al. (2003), there is no standard and generally accepted models. Some authors consider that these effects are specific to the land-cover type (Richter, 1998; Riano et al., 2003), others neglect the directional effect of the land-cover type (Shepherd and Dymond, 2003). As most of these models have been developed for high spatial resolution satellite images (10 to 30 m), we can assume that the authors lacked information on the directional effects in such kind of images. The study we presented on multi-view angle data may provide more insight on directional effects to improve topographic effect correction models. However, these models are namely intended to radiometry normalisation. How to deal with texture distortions due to topographic effects? This is a challenge for texture analysis of forest images in hilly regions, especially aerial photographs and VHSR satellite images.

*... Give me a place to stand, and I shall move the Earth.*

(Archimedes)

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