Application of satellite remote sensing for land use statistics

Methods and results of a research project

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Application of satellite remote sensing for land use statistics

Methods and results of a research project

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Summary

In order to determine the benefits of satellite remote sensing in land use statistics, a cooperation was sought by the Swiss Federal Statistical Office with the Department of Geography at the University of Zurich. In 1990, the first research contract was signed, which was followed by four further projects until 1997. The present publication is a summary of the used methods and the results achieved during these five project phases. More detailed descriptions and technical information can be taken from intermediate and final reports, as well as seminar documentations.

The research was carried out in two different research areas. One area was defined by the map sheets of Zug, Rigi and Beckenried, and the other area was the region of Yverdon. In total, 13 satellite images were obtained. They comprised nine Landsat-5 TM scenes, one SPOT-2 Pan, one SPOT-2 XS, and two SPOT-3 XS scenes. An evaluation, using the available TM scenes from the years 1985-1996, showed that about 80% of the surface of Switzerland can be covered annually with a suitable TM scene. Furthermore, it is possible to cover the entire surface of Switzerland with at least two suitable TM scenes every three years on average.

Due to the fact that standard commercially available, unprocessed satellite image data is only moderately suitable for classification and statistically reliable evaluation, as well as cartographically satisfactory presentation, it was necessary to develop and carry out preprocessing steps. It was found that certain TM data needed the following two corrections: the removal of duplicated lines and the removal of local noise. No such post-system corrections were necessary for SPOT data.

The next step is to carry out an orthorectification, since imaging sensors do not collect data parallel to the national coordinate system and high-relief terrain causes distortions in the image. A number of different methods are described in this publication. They are all based on ground control points, which must be determined in the image on the basis of a national map. The more precise the ground control points are, the closer the geometrical correspondence of the orthorectified scene to the national map. Research showed that an accuracy of a half pixel can be achieved with well-defined ground control points.

Depending upon the application, it is advisable to carry out a radiometric correction of the scene. Thereby, it is attempted to compensate the scene-dependent radiometric effects in the satellite image. They can be caused by the varying topography (e.g. various angles of solar incidence, shadows) and the atmosphere (e.g. differing degrees of haze). A number of possible correction approaches are suggested. However to date, it has not been possible to find a convincing correction for all types of errors. Depending upon the type of classification, it is nonetheless advisable to carry out a radiometric correction.

Apart from using the spectral channels of the satellite data for classification, information from the elevation model (elevation, slope, aspect), as well as textural information was used. Both the selected features as well as the selected classification algorithm have an influence on the quality of the result. However, the ideal configuration is dependent upon the classification problem, the research area, and acquisition date of the satellite data. Therefore, a method which is generally valid for all situations cannot be determined.

Finally, a number of results achieved during the research project are presented. In each case, the results are accompanied by details of the selected scenes, the applied corrections, the selected classification algorithm and the respective classification accuracy obtained

against the ground reference. When stating the classification accuracy, it is assumed that the ground reference is 100% correct. However, this assumption is almost never totally true. Differences may occur, in particular, due to the differing acquisition dates or differing geometries between the ground reference and the satellite data. The indicated accuracy is therefore usually underestimated.

In view of the project results, the Swiss Federal Statistical Office was in the opinion that the know-how should be used and that the land use statistics should be supplemented by satellite remote sensing in the field of forest type composition. This work will be completed by the end of the year 2000. A separate publication on this subject is planned.

Condensé

Quelle pourrait être l'utilité de la télédétection par satellite pour la statistique de la superficie? Pour le savoir, l'Office fédéral de la statistique s'est associé avec l'Institut de géographie de l'Université de Zurich. Ce dernier s'est ainsi vu confier en 1990 un premier mandat de recherche, suivi de quatre autres jusqu'en 1997. La présente publication donne une vue d'ensemble des méthodes appliquées et des résultats obtenus au cours des cinq phases de ce projet. Les rapports intermédiaires, les rapports finaux et les dossiers de cours publiés dans ce cadre contiennent des descriptions et des données techniques détaillées.

Les études ont été réalisées sur deux régions différentes. L'une d'elles correspondait aux cartes nationales de Zoug, du Rigi et de Beckenried, l'autre à la région d'Yverdon. Au total, 13 images ont été achetées. Parmi celles-ci, on trouve 9 images Landsat-5 TM, une image SPOT-2 Pan, une image SPOT-2 XS et deux images SPOT-3 XS. Une étude réalisée à partir des images TM existant pour les années 1985 à 1996 a montré que pendant cette période, on disposait chaque année d'images utilisables pour près de 80% de la surface de la Suisse. En outre, on obtient tous les trois ans en moyenne au moins deux images TM de qualité suffisante pour permettre une représentation de l'ensemble de la Suisse.

Telles qu'elles sont proposées à la vente, les données provenant de satellites ne sont utilisables que dans certaines limites pour procéder à des classifications détaillées et à des exploitations statistiques fiables, ainsi qu'à des représentations cartographiques satisfaisantes. Il a donc fallu mettre au point une méthode de prétraitement, qui a été appliquée aux images provenant des deux satellites. Pour certaines images de type TM, deux sortes de correction se sont avérées nécessaires: il a fallu éliminer certaines lignes à double et supprimer le bruit de fond local. Pour les données de SPOT, un tel traitement n'a pas été nécessaire.

Les capteurs n'enregistrant pas les pixels parallèlement à l'axe des coordonnées géographiques, et le relief du terrain présentant des distorsions, on a ensuite dû procéder à une orthorectification. Cette publication présente différentes méthodes à cet effet. Toutes recourent à des points de calage, qui doivent être déterminés à la fois sur l'image et sur une carte. Plus la qualité des points de calage est bonne, et plus la géométrie de la scène orthorectifiée correspond à celle de la carte topographique. Les études montrent que lorsque les points de calage sont de bonne qualité, on peut obtenir une précision équivalant à un demi-pixel.

Suivant l'utilisation de l'image, il est recommandé de la soumettre encore à une correction radiométrique. Lors d'une telle correction, on s'efforce de compenser, sur l'image satellite, les effets radiométriques pouvant être induits par la topographie (angle d'ensoleillement variable, ombrages, etc.) ou par l'atmosphère (variations des conditions de brume p. ex.). Différentes solutions ont été présentées en vue de corriger ces problèmes, mais aucune ne s'est jusqu'ici avérée en tout point convaincante. Certains modes de classification demandent néanmoins une telle correction.

Pour la classification, on utilise, en plus des bandes spectrales des données satellites, des informations relatives au modèle de terrain (hauteur, inclinaison, exposition) et des informations sur la texture, calculées à partir des différents canaux. Le choix des caractéristiques comme celui de l'algorithme influent sur la qualité des résultats. Mais pour obtenir une configuration optimale, il faut tenir compte du problème de la classification, de la région considérée et du moment où l'image est prise. Il n'existe donc pas de méthode répondant à tous les besoins.

Enfin, cette publication présente quelques-uns des résultats obtenus dans le cadre du projet de recherche. Chaque exemple est accompagné d'un commentaire indiquant les scènes utilisées, les corrections apportées, l'algorithme ayant servi à la classification et la précision de cette classification par rapport à une référence au sol. Pour cette dernière comparaison, on admet que la référence au sol est correcte à 100%. Toutefois, cette condition est quasiment impossible à remplir. Des distorsions peuvent résulter notamment des différences relatives aux dates ou aux heures des prises de vue ou de variations géométriques entre la référence au sol et les données du satellite. La valeur indiquée sous-estime donc quelque peu la précision effectivement atteinte.

Au vu des résultats de ces travaux, l'Office fédéral de la statistique estime qu'on peut reprendre le savoir-faire développé dans le domaine de la télédétection par satellite pour compléter la statistique de la superficie au niveau de la couverture forestière (distinction feuillus-conifères). Les travaux en question s'achèveront en l'an 2000. Ce thème fera l'objet d'une publication séparée.

1 Introduction

1.1 The task

The method of aerial photo interpretation of systematically distributed sample points, used operationally by the Swiss Federal Statistical Office, was developed in the 1970s for the survey of a new land use statistics of Switzerland. It was applied to the first inventory of land use from 1979 to 1985 [68]. It was also used in the first extensive update from 1992 to 1997. Above all, and especially in regard to the monitoring of land use of permanent sample points, this method has proven to be unexpectedly time-consuming. In addition, it has revealed weaknesses regarding identification and accuracy of certain categories, as well as achievable actuality and temporal comparability. The results are, though statistically very exact, only of limited use for the preparation of thematic maps and spatial analysis.

In recent years, satellite remote sensing has developed rapidly, and thereby the potential of satellite data for earth observation has been enormously increased. Despite many possibilities of use, this potential has rarely been used in practice and for operational and production-oriented tasks. While significant progress has been made in the field of research and development, there is a gap between potential use and effective, operational application.

1.2 The research project

In 1990, the Swiss Federal Statistical Office initiated a research project, in order to evaluate the possibilities of using satellite remote sensing in official statistics, namely those of land use and environmental statistics. The Department of Geography at the University of Zurich, under the supervision of Prof. Dr. K.I. Itten, was commissioned to carry out the necessary studies to fulfil this task. In five project phases, methods were elaborated and tested for different subject matters of satellite remote sensing.

In the first project phase, starting from December 1990, the methodical bases of geometric and radiometric correction of satellite imagery were studied. During this phase, procedures to correct terrain-induced distortions and sensor-related radiometric effects were developed. Ehrler [25] carried out these analyses using Landsat TM and SPOT HRV (XS and Pan) images, in which he concentrated on a research area in central Switzerland (map sheets Zug, Rigi, Beckenried). It was shown that striping in SPOT images can be corrected to a large extent with the help of a morphological filter without any loss of information. In regard to geometrical accuracy, the requirements of the Swiss land use statistics could be met with Landsat TM, as well as with SPOT HRV.

In the second phase, which started in October 1992, a concept was developed for the radiometric correction of illumination differences. Furthermore, the potential of satellite data was examined for automatic, digital land use classification. For these tasks, the research area and data base from the first phase were used. It was shown that illumination differences could not be corrected sufficiently with the help of conventional empirical and semi-empirical correction methods, in order to significantly improve classification accuracy. Examinations of the spectral separability of the land use categories have shown that differentiation of the four main classes “wooded areas”, “agricultural areas”, “settlement and urban areas”, and “unproductive areas” is seldom possible based on the spectral information alone [12].

Phase III, which started in January 1994, included three main topics: (1) the differentiation of the total forest area into deciduous, mixed and coniferous forest (forest types), (2) the elaboration of a concept for the differentiation between arable land, meadow and pasture, and (3) the generation of the best possible satellite image classification for a sample map sheet at the scale of 1:25’000. As an innovation in the pre-processing of satellite data, the raw data was radiometrically corrected with the help of a physical model of Sandmeier [54]. The comparison of different forest ground truth data with the classified image for the research area of Beckenried showed considerable differences and pointed to the principle question of the reliability of such sources. For the satellite image classification in western Switzerland, a new Landsat TM scene was purchased and the region Yverdon was selected as research area. The comparison of classification with land use statistics has shown that despite using advanced methods, no satisfactory results for the categories “industrial areas”, “buildings” and “vineyards” could be achieved [12].

Phase IV began in January 1995 and followed three aims: (1) the realisation of the concept for multitemporal classification in agricultural areas established in phase III, (2) planning and assistance of multitemporal satellite image acquisition, and (3) consultation and conceptual support in establishing a project draft for a practical and production-oriented application of satellite remote sensing [13]. Field surveys were carried out in the Yverdon area, which consisted of very detailed information on agricultural crops in different test areas. In addition, seven Landsat TM and two SPOT HRV (XS) scenes were obtained within the same vegetation period. The multitemporal classification in the agricultural area resulted in a significant improvement as compared to the monotemporal classification. By extending consultation services, the methods, procedures and programmes developed, as well as the experience gained regarding a practical and production-oriented application was transferred to the Swiss Federal Statistical Office.

Phase V was initiated in May 1997. The main topics were the examination of the overlapping area of Landsat TM satellite scenes for the improvement of classification, as well as the analysis of multitemporal satellite data in the transition area between forest and certain agricultural areas. For the Yverdon research area, it was shown that additional spectral information in the overlapping area of two scenes resulted in significant improvement of the classification. Based on the examinations in the transition area to the forest, the significance of non-spectral additional data such as topography and texture was shown. In addition, it became evident that the methods of neural networks are particularly suitable for such complex classification problems.

1.3 Aim of the report

The results of these five project phases are documented in 16 reports and eleven presentations. However a summary, giving an overview of the examinations, does not exist.

This methodical volume on remote sensing volume should fill the gap and summarize the methods and results established within the framework of this project between 1990 and 1998. The examined methods and results will be outlined and assessed in an integrated context. The most important results of the classification will also be presented. It is not the aim of this volume to deal with the different phases of the project. Similarly, the methods and their algorithms will not be described in detail. Reference to the specific literature and project reports will be made for this purpose.

1.4 Structure of the report

Chapter 2 deals with the basis of remote sensing. The development and application of remote sensing will be shown. The satellite systems and data used in this project will be described and the available land use data in Switzerland will be introduced (official land use statistics). Finally, questions about the ideal acquisition time and the availability of cloudless satellite data in Switzerland will be discussed.

Chapter 3 forms the main part of this volume. It deals with the methods used in the land use statistics project for preprocessing and classification. After an overview of the existing methods is given, the individual procedures will be described and their results will be summarized and assessed.

The subsequent chapter with results supplies examples of the land use classifications. All the necessary processing steps are listed.

A summary of technical terms, a list of abbreviations, as well as the bibliography are found at the end of this volume.

2 Basis

2.1 Development of remote sensing

In recent decades remote sensing has become increasingly important in many areas of geoscience. Its application can be found in the fields of agriculture, forestry, geology, oceanography, hydrology and meteorology. Until the beginning of the 1970s aerial data acquisition was mainly used. Satellite images were reserved for military use. Since the launch of the first American Landsat platform in 1972, satellite data acquisition has been available for civil purposes as well.

Remote sensing sensors measure reflected or emitted radiation from different spectral ranges of visible light, infrared as well as microwaves. Thus, photographic and non-photographic data collection systems can be differentiated. Usually a multitude of individual measurements is combined to an image (e.g. scanner). In certain cases an acquisition can also be a single measurement (e.g. radar altimeter [40]).

Photographic acquisition systems remain the most common and normally consist of a camera and a film. For conventional aerial photography a single-lens camera (aerial survey camera) is almost always used. In addition, there are multi-lens cameras, aerial strip cameras and panorama cameras. While previously black and white film was used almost exclusively, the interpretation possibilities have now been extended due to colour, IR and UV films.

Non-photographic, digital acquisition systems are growing in importance. Depending on the technology, these systems are referred to as scanners, radiometers, radar or spectrometers. In particular the use to which remote sensing data can be put has been considerably increased by multi- or hyperspectral data collection, which are characterised by the simultaneous registration of radiation in different spectral ranges. The laser scanner has a special place in this context. With the help of this sensor, the distance between the platform and the terrain surface can be determined. This information can be used to produce high precision digital elevation models (DEM).

The interpretation of remote sensing images was previously based on analogue methods. Thus, photogrammetric analysis, as well as interpretation based on grey or colour toning, texture, pattern, and – in the case of stereoscopic view – the three-dimensional characteristics of the surface forms predominated. With the advent of electronic data processing in the 1960s, methods of automatic interpretation were developed additionally.

2.2 Use of satellite remote sensing

The use of satellites can be valued as one of the most important technological achievements determining the current state of remote sensing. Information acquired from satellites has become indispensable, especially for meteorological applications. A further important use can be found in the field of land cover or land use. In principle, remote sensing data can be used in four areas:

- mapping,
- inventoring,
- monitoring,
- forecasting.

The aim of mapping is the production of a land use or land cover map [2, 3, 36]. Using manual or automatic procedures, the pixels of an image are allocated to a category, whereby the mapping accuracy is of foremost importance. As a measure of quality, a pixel-to-pixel comparison of the result with the ground truth is often carried out.

During inventoring, the area of individual types of land use is determined [10, 29]. With the help of statistical methods – e.g. regression estimates – the accuracy of conventional, usually ground-based procedures, is improved by satellite data. The quality of the result is expressed by the correlation between ground truth and satellite data.

During monitoring, the observation of land use changes is important [31, 59]. Usually data taken from different times are used. A typical example would be the monitoring of forest areas in the tropics.

During forecasting, attempts are made to predict future developments in land use [19, 58]. These prognoses can be based on mono- or multitemporal data. For early recognition of pest affliction or drought in agricultural areas, monotemporal data are usually used. Harvest forecasts on the other hand are often based upon multitemporal data.

2.3 Swiss land use statistics

In the years 1912, 1923/24, 1952 and 1972 land use statistics were published, which, for various reasons, were methodologically inconsistent and thus were not applicable for many tasks, particularly for comparisons over time. Therefore on 17 February 1982, the Swiss government decided on a new examination of land use statistics. This was done with the help of aerial photograph interpretation of regular sample points, a method developed at the end of the 1970s at the Institute for Photogrammetry of the Swiss Institute of Technology (ETH) Lausanne and the Institute for Local, Regional and Federal Planning of the ETH Zurich with the assistance of various federal agencies.

Black and white aerial photographs from the years 1979 to 1985 from the flight programme of the Federal Office of Topography served as data basis for the land use statistics 1979/1985. The data set 1979/85 therefore represented the condition of land use in Switzerland at the beginning of the 1980s, whereby the oldest data come from 1979 (western Switzerland) and the most recent from 1985 (the canton of Graubünden). The acquisition of data, which was organized according to the sheets of the federal map 1:25’000, began in the spring of 1984 and was concluded at the end of 1992.

For this, nearly 4000 transparencies with a net of sample points at a distance of 100 m × 100 m were calculated and superimposed onto the aerial photographs. As far as the positions of the sample points were concerned, the intersections of the 100 m coordinates of the federal map were decisive. With the help of the orientation elements of the aerial photograph (projection centre, focal length, tilt of photograph, principal point), and the Federal Ministry of Defence’s digital elevation model RIMINI which was converted to hectare resolution and expanded to the east of Switzerland, the positions of the sample points for each aerial photograph were subsequently calculated and marked. As a result, a solid transparency was obtained showing the terrain-adjusted point sample net, frame marking, ground control points and kilometre labelling, which could be superimposed upon the relevant aerial photograph slide for the purpose of interpretation.

The interpretation of land use was carried out under stereoscopes, which allowed the three-dimensional analysis of the images. Each of the 4.1 million sample points was allocated to one of 69 categories of the land use catalogue. The decisive factor in the allocation of the land use codes was the land use at the sample point. In order to standardize the interpretations and prevent misunderstandings with the allocation criteria each image was checked, point for point, by a second interpreter. Any differences were subsequently discussed and clarified. Unclear land use or areas which proved difficult to interpret, as well as any remaining open individual points were verified and allocated conclusively during field inspections. The result of the interpretation work – the corrected sample films with land use codes – were computerised and incorporated in the geographic information system (GIS) of GEOSTAT of the Swiss Federal Statistical Office for analysis [11].

The land use statistics nomenclature is principally defined by two frequently interrelated parameters, that is by the type of ground cover (vegetation, buildings, water etc.) and its function (agriculture, settlement, industry, recreation etc.). This categorisation is not a consistent hierarchical system in the sense that the cover occupies the highest position and the lower levels are reserved for its function. For methodical and practical reasons, a mixed system is used.

The basic categories were determined on the basis of an opinion poll amongst the administration and the most important users of the statistics and subsequently tested in six areas. Experience gathered in the course of the examination led to initial changes and adjustments. On the one hand, categories had to be dispensed with, e.g. meadow, since they were not always recognizable because of seasonally divergent photo flights. On the other hand, where obvious land use did not fit easily into any catalogue category, additional categories were created. A detailed description of the basic categories can be found in the category catalogue of the Swiss Federal Statistical Office [12].

2.4 Description of the satellite sensors used

Landsat TM

The first Landsat satellite was put into orbit in 1972. Since then, five further satellites have been successfully launched. The first generation of these satellites, Landsat 1 to 3, had two sensors on board: the RBV video camera and the MSS opto-mechanical scanner. As a result of technical problems with the RBV and the spectral and radiometric superiority of the MSS, RBV data were only seldom used. The second Landsat generation appeared in 1982 with the launch of Landsat 4 and continued with Landsat 5 in 1984. Both platforms, in addition to the MSS, have the TM scanner on board. The planned mission length for Landsat 4 and 5 was originally three years. According to present estimates, however, the continuity of the Landsat 5 mission could be maintained beyond 2000 [26]. Landsat 6 should have been operative in 1993, however the satellite was lost shortly after launch. Landsat 7 was put into orbit in April 1999. This platform is equipped with an improved TM (ETM+) as well as with the new HRMSI. The ETM+ instrument is a multispectral scanner with eight bands.

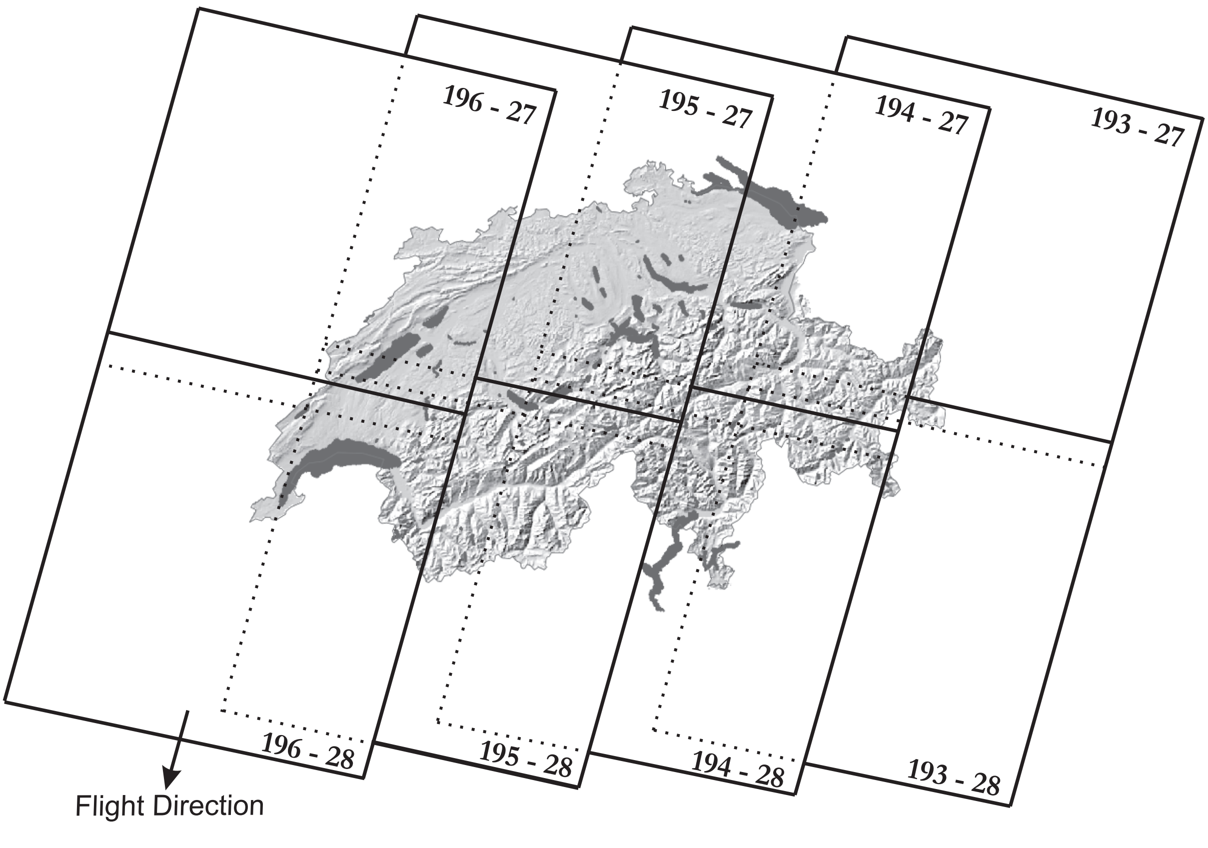
Landsat 5 has a near-polar, sun-synchronized orbit at an average altitude of 705 km. It crosses the equator between 09:20 and 09:40 LST at an inclination of 98.2° and it needs 98.9 minutes to circle the earth. A complete coverage of the earth between 81° N and 81° S is the result. After 16 days, the satellite reaches its starting point in orbit again. The sideways overlap of two neighbouring tracks amounts to 7.6% at the equator, increasing in the direction of the poles. At the geographical latitude of Switzerland, the overlap amounts to 38%, at 60° it is 54%. Over 80% of Swiss territory is thereby covered by two tracks, greatly increasing the availability of usable data.

The TM sensor has seven bands with a spatial resolution of 30 m and 120 m (Table 1). The scan width is 185 km.

Table 1: TM band specifications

Band	Spectral range [μm]	Spatial resolution [m^2]
TM 1	0.45 - 0.52 (VIS, blue)	30 × 30
TM 2	0.52 - 0.60 (VIS, green)	30 × 30
TM 3	0.63 - 0.69 (VIS, red)	30 × 30
TM 4	0.76 - 0.90 (NIR)	30 × 30
TM 5	1.55 - 1.75 (SWIR)	30 × 30
TM 6	10.4 - 12.5 (TIR)	120 × 120
TM 7	2.08 - 2.35 (SWIR)	30 × 30

Figure 1: The WRS II of Landsat TM in Switzerland. Source: [49]



The company Eurimage distributes Landsat data from Europe, North Africa and the Middle East. The data are registered at three different ESA ground receiving stations: Fucino (Italy), Kiruna (Sweden) and Maspalomas (Spain). Switzerland lies in the reception area of Fucino and Kiruna.

There are two reference systems for Landsat: WRS I for Landsat 1, 2 and 3 and WRS II for Landsat 4 and 5. The point of intersection between track and frame forms the nominal scene centres and are used for the identification and ordering of the Landsat data (see Figure 1).

SPOT HRV

Since the launch of SPOT-1 in 1986, SPOT data have been operationally available. In the meantime, three further platforms have become operational: SPOT-2 (1990), SPOT-3 (1993) and SPOT-4 (1998). These SPOT satellites are each equipped with two HRV opto-electronic line cameras. These sensors measure in four, respectively five different bands. Two satellites are always in use. For example, when SPOT-3 was unexpectedly lost in November 1996, SPOT-1 was reactivated.

The quasi-polar, sun-synchronized orbits of the SPOT satellites are at an average altitude of 832 km and have an inclination of 98.7°. They require 101.4 minutes to circle the earth and reach their starting point after 26 days. The equator is overflown between 10:20 and 10:40 LST.

The viewing angle of both HRV sensors can be adjusted ±27° perpendicular to the flight direction with the help of a remote-controlled mirror. This technique allows the survey of any area within a strip of approximately 900 km per track, and can be used for a higher temporal resolution as well as for stereo analysis. As a result, a certain area at the equator can be scanned seven times within the repetition cycle of 26 days. At the geographical latitude of Switzerland, this results in a maximum coverage of eleven scenes within 26 days. This is equivalent to an average temporal resolution of 2.4 days at a maximum interval of four days. Both instruments can be operated independently of each other in either panchromatic (Pan or P mode) or in multispectral mode (XS mode) and each has a scan width of 60 km (Table 2). During parallel operation in the same mode, the sideways overlap area is 3 km, leading to a total scan width of 117 km.

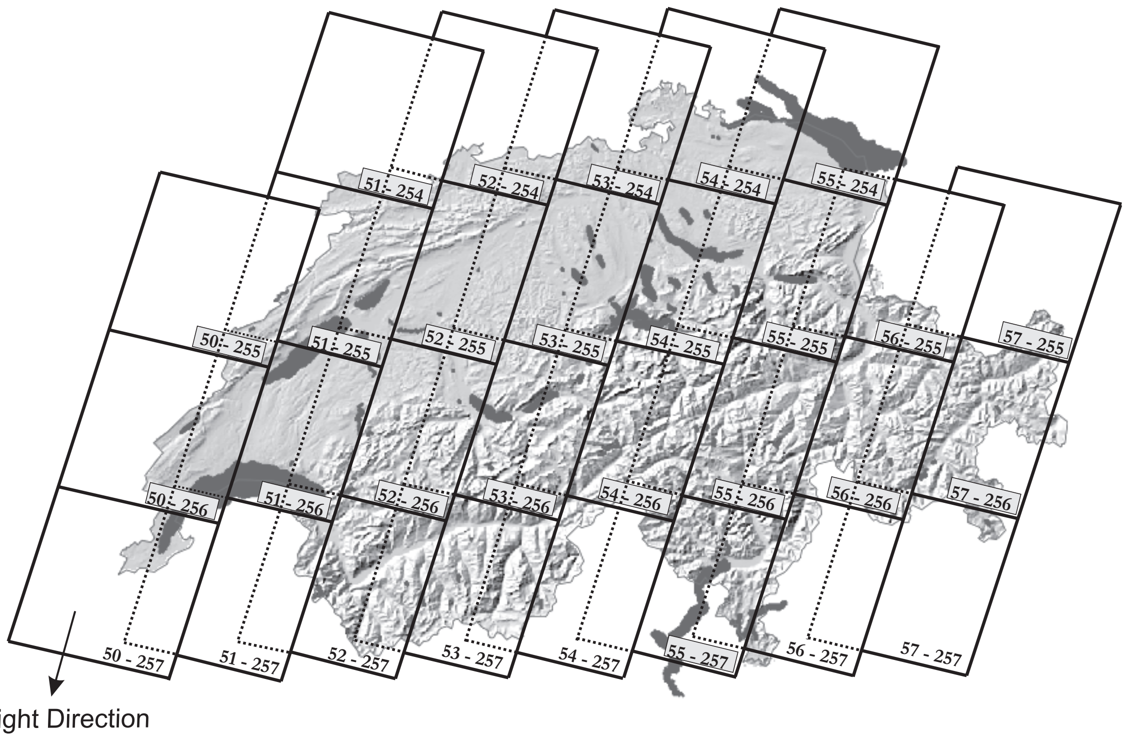
Table 2: HRV band specifications

Band	Spectral range [µm]	Spatial resolution [m^2]
P	0.51 - 0.73 (Pan)	10 × 10
XS 1	0.50 - 0.59 (VIS, green)	20 × 20
XS 2	0.61 - 0.68 (VIS, red)	20 × 20
XS 3	0.79 - 0.89 (NIR)	20 × 20
XS 4 (SPOT-4 only)	1.58 - 1.75 (SWIR)	20 × 20

In Europe, SPOT data are registered at the following ground receiving stations: Toulouse (France), Kiruna (Sweden), Fucino (Italy), and Maspalomas (Spain). With the exception of Maspalomas, Switzerland lies in the reception area of all of these stations.

The SPOT reference system, as with the Landsat, is composed of tracks and frames (see Figure 2)

Figure 2: The reference system of SPOT in Switzerland. Source: [49]



2.5 Optimal acquisition date

The optimal acquisition date of satellite data depends on a number of factors, the most important being

- the illumination situation and
- the spectral differentiability of the categories.

According to the task and research area, snow cover must also be taken into consideration when choosing a favourable acquisition date.

These two influences can hardly be viewed separately from one another. The following empirical investigations therefore only give an indication as to the optimal acquisition date. For a definitive opinion, more extensive investigations are necessary.

2.5.1 The illumination situation

The illumination situation plays a special role in Switzerland. With decreasing solar elevation the areas with shadow and low illumination increase. Faulty classification can be reduced, but not avoided, in these areas by correcting the illumination effects.

Leiss [46] empirically examined the optimal acquisition period for land use classification in the Yverdon research area with the help of TM-scenes from April, May, June, July and October 1995. It was shown that the accuracy of the maximum likelihood classifications from

April to July varied between 78% and 81%, while the accuracy of the October classification was 74%. Following the good results achieved in the investigations by Dousse [22] with the help of September data, it can be assumed that the deterioration in the accuracy of the classification with the October data can be traced back to the poor illumination conditions.

Regarding the illumination situation, an acquisition date between April and September is recommended for general land use classification.

2.5.2 Spectral differentiability

The optimal acquisition date in regard to spectral differentiability is dependent on the task. A scene can thus be most suited to differentiate certain agricultural cultures, e.g. barley and wheat, whilst this acquisition date does not allow for the optimal recognition of different degrees of forest mixture.

Dousse [22] empirically examined the optimal acquisition date. The examined area of Yverdon offered eight images: a TM scene for each month from April to October 1995 as well as a SPOT XS scene for July 1995. The classification of nine different categories (mainly agricultural areas) with the maximum likelihood algorithm show that the best accuracy could be achieved with the help of the TM data from September.

As far as spectral differentiability is concerned, the period between April and October appears to be a favourable acquisition date for agricultural areas.

2.6 Availability of cloud-free satellite data of Switzerland

The availability of satellite data is a basic requirement for satellite remote sensing applications. This depends fundamentally on three factors:

- error-free operation,
- temporal resolution of the acquisition system,
- cloud cover of the research area in the case of VIS and IR systems.

While the temporal resolution of an acquisition system is usually constant, the degree of cloudiness can show strong spatial and temporal variation.

Cloud cover is the most limiting factor for the availability of data in the VIS and IR range in Switzerland. Within the desired acquisition period, it is rarely possible to obtain a cloud-free satellite image. In practice therefore, partly cloudy data are often used. Although there are statistical methods to reduce the problem of cloudy parts in images [32, 56], the quality of the result is generally affected.

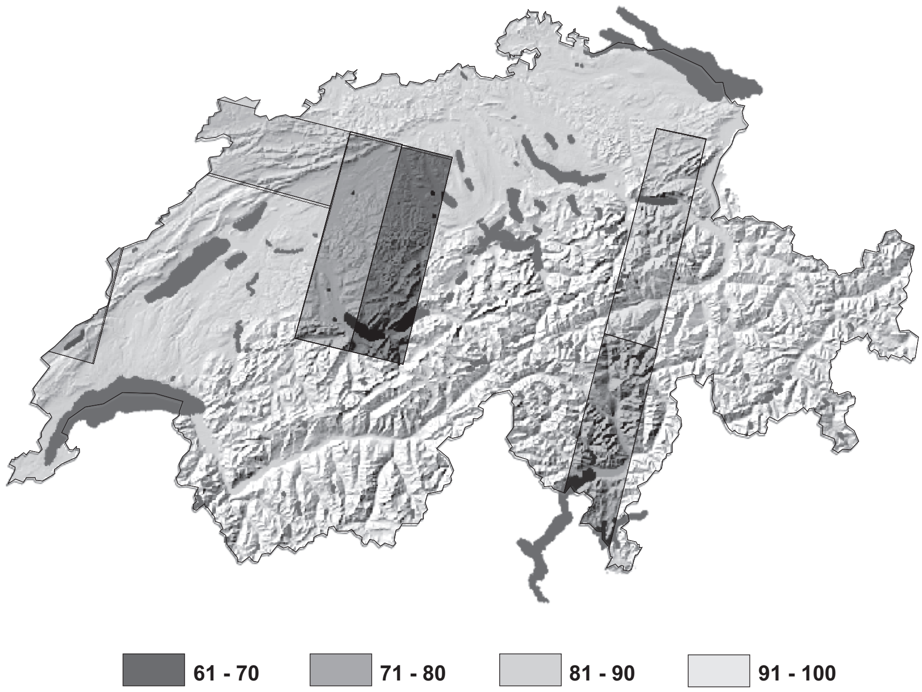
Leiss [46] has examined the availability of satellite data with minimal cloud cover in Switzerland. The Landsat TM data registered in the LEDA catalogue from Eurimage served as the basis for the investigation. From this data base the scenes were extracted which cover Switzerland (track 193 to 196 and frame 27 to 28, cf. Figure 1) and were taken between 1985 and 1996. In total, 2834 scenes were at the disposal of the examiners.

In choosing suitable data it was assumed that only quarter scenes would be used. The decision as to the suitability of a quarter scene for a land use classification was based on the following criteria:

- acquisition date: 1st April to 31st October,
- degree of cloudiness: < 20%,
- time interval to the last scene: > 20 days.

As a measure of quantifying availability, the expectancy value, following Kontoes et al. [39], was used with which an appropriate scene can be registered. This estimated value results from the percentage of the years from which a sufficient number of quarter scenes are available. Figure 3 shows the availability of at least one virtually cloud-free scene within a year.

Figure 3: Availability of at least one suitable scene (in percent)



The results of this analysis permit the following statements: approximately 80% of the surface area of Switzerland can be covered annually by at least one suitable TM quarter scene. The lowest availability (67%) is to be found in the area between Lake Sempach and Lake Thun, which is covered exclusively by track 195. This area, however, covers less than 5% of the country‘s territory.

The investigations of Leiss [46] have also revealed that it is possible to cover the total area of Switzerland with at least two suitable TM data records on average every three years (availability 33%). The most difficult data to obtain appears to be for the area to the north and south of Lake Walen. This study has shown that the overlap area of neighbouring scenes has a very decisive influence on the availability of suitable scenes. In addition, there are more suitable data available for areas south of the Alps, as well as for the Lake Geneva region, than for areas north of the Alps. It is becoming clear that a multitemporal analysis in Switzerland, which requires at least three scenes within the period of cultivation, is no longer possible with Landsat TM alone. The use of multiple sensors is therefore unavoidable.

2.7 Satellite data used

Table 3 below shows all satellite data purchased and used in the project. Quicklooks of these scenes are shown in Figure 4 in the centrefold.

Table 3: Landsat and SPOT data used

Date	Sensor	Track/Frame	Scene Type	Cloudiness	Contained research areas
09.08.90	TM	195 / 027	Full scene	1-10%	Yverdon, Zug, Rigi, Beckenried
30.06.91	Pan	054 / 255	Full scene	0%	Zug, Rigi, Beckenried
30.06.91	XS	054 / 255	Full scene	0%	Zug, Rigi, Beckenried
11.07.91	TM	195 / 027	Full scene	11-20%	Zug, Rigi, Beckenried
08.04.95	TM	196 / 027	Quarter scene	0%	Yverdon
03.05.95	TM	195 / 027	Quarter scene	1-10%	Yverdon
20.06.95	TM	195 / 027	Quarter scene	0%	Yverdon
19.07.95	XS	050 / 255	Full scene	0%	Yverdon
22.07.95	TM	195 / 027	Quarter scene	0%	Yverdon
14.08.95	TM	196 / 027	Quarter scene	31-40%	Yverdon
24.09.95	TM	195 / 027	Quarter scene	11-20%	Yverdon
17.10.95	XS	050 / 255	Full scene	0%	Yverdon
17.10.95	TM	196 / 027	Quarter scene	21-30%	Yverdon

3 Methodology

3.1 Post-system correction

3.1.1 Overview

Satellite data transmitted to earth are full of sensor-related radiometric and geometric errors. The system correction usually carried out by the provider rectifies most of these errors or at least reduces them. Those remaining have to be determined by the user within the framework of a post-system correction and, if needed, have to be corrected. This is known as quality analysis of the data. Based on the different sensor technologies and system corrections, the possible errors in the TM and HRV data are different and call for a sensor-specific assessment.

Darvishsefat [18] summarised and analysed the main errors in TM data. According to Darvishsefat, the main errors in TM data are the following:

- line duplication,
- column duplication,
- line segment displacement.

Besides these the following radiometric errors are crucial:

- local noise,
- calibration residual error,
- memory effect.

Ehrler [25] tackled the problem of quality analysis of SPOT XS and Pan. He found mainly the following radiometric errors in HRV data:

- calibration residual error,
- local noise.

The errors examined within the framework of the land use statistics project are presented below. For each parameter of influence there follows a description, a reason for its cause, an estimation of its magnitude, the explanation of possible correction methods as well as an evaluation regarding an improvement of land use classification.

3.1.2 Line duplication in TM

In the TM data system-corrected by ESRIN, line duplications appear on an irregular basis. This redundant information is to be found in all bands at the same place and was introduced to correct changes in altitude and flight speed in regard to the IFOV of the sensor [24].

During geometric correction duplicated lines lead to local inaccuracy in the magnitude of a pixel. In the case of regular appearance they can be eliminated without any difficulties, since the geometrical transformation used balances out the produced change of scale [46].

This elimination was carried out for all TM scenes used in the project.

3.1.3 Duplicated columns and line segment displacement in TM

Columns are duplicated during system correction by ESRIN for two reasons: on the one hand, the earth's curvature and perspective distortion (panorama effect) is compensated, and on the other hand, fluctuations in the rotation velocity of the scanning mirror are balanced out. This is also the reason why column duplication occurs separately within a sweep [24].

Since the rotation velocity of the scanning mirror can only be unsatisfactorily adjusted, there is the occasional line segment displacement of one pixel at the transitions between the sweeps [24].

Investigations of Darvishsefat [18] have shown that duplicated columns should not be removed from the data because otherwise significant errors appear in the geometrical correction. Therefore all duplicated columns were left in the used TM scenes of the project.

3.1.4 Local noise in HRV and TM

Local noise is the consequence of data transfer errors, of sudden detector saturation or other electronical problems. The pixels concerned have a grey value of 0 (in the case of data transfer errors) or 255 (in the case of saturation). Depending on the sensor technology, this error appears in TM data in lines, in XS data in columns.

Spatial correlation is a method to automatically detect noisy pixels [57]. This procedure is based on the expectation that neighbouring pixels show similar grey values. The squared difference between neighbouring lines can be used as a measurement of similarity. With the help of a threshold value, noisy and non-noisy pixels can be distinguished. This method is suitable above all for images strongly affected by local noise. However, this does not completely prevent non-noisy pixels from being detected.

Another possibility to detect noise is by manual digitalisation at the screen [46]. This method is very reliable. Because this method is very time consuming, it is only suitable when the number of noisy pixels is not too high.

Affected pixels lead to errors in the classification and therefore correction is recommended. Generally, manual detection of affected pixels is more suitable than automatic detection, as only few pixels are affected by this effect.

For the correction of noisy pixels a median filter is suitable. The window size has to be matched to the number of the concerned pixels. For TM window sizes of 1×3, 1×5 or 1×7, for HRV 3×1, 5×1 or 7×1 are suitable.

In the data used in the project, local noise in the research area was detected only in the TM scene of 08.04.95. This was corrected with the method described. In all other HRV and TM data this correction was unnecessary [46].

3.1.5 Calibration residual errors in HRV

Striping originates in HRV data due to the different calibrations of the 1728 detectors within an array and is characterised by a striping in column direction. The variation after the system correction is in the range of one to two grey values [25].

Using a morphological filtering after Banon et al. [4], striping can be effectively corrected in level 1A as well as in level 1B data [42]. The use of this correction method achieved no significant improvement in classification in the examined XS data, for this reason it can be dispensed with for operational use [46]. Within the project framework, striping was corrected only in the XS and Pan scene of 30.06.91 [25].

Due to the different calibration between the four arrays, a type of banding occurs at the transitions. Ehrler [25] discovered that after successful system correction the variations originating from these errors reached one to two grey values. There is almost no possibility of correction for this effect. However, since the dimension of the error lies within the striping range, it can be assumed that disregarding the error will not decisively affect the result of the classification.

3.1.6 Calibration residual errors in TM

The dissimilar calibration amongst the individual detectors is visible in TM data within the 16 detector elements of a sweep. This error can not be totally eliminated by system correction and shows itself in the image as a striping in line direction [48, 28].

Darvishsefat [18] determined that after system correction the differences between the line means were less than a grey value. A correction of this error can therefore not lead to the improvement of a classification, and for this reason, it can be dispensed with for operational use.

Therefore, a correction of striping in the TM data used was rejected.

Through the dissimilar calibration of the 16 detectors during forward and reverse movement banding between the sweeps occurs, which is still visible after applied system correction [48].

For the correction of banding, the generation of sum histograms of all image lines and the following replacement of digital numbers with deviations of more than two proved to be worthwhile [60]. Since this correction is only meaningful in the TM bands 1 and 5 [18], and even its use showed no improvement of a digital classification, this error does not need to be corrected for operational use.

A correction of banding was not carried out for any of the TM scenes used.

3.1.7 Memory effects with HRV and TM

If the sensor scans over strongly reflecting areas (e.g. snow, ice or cloud) and then over areas with less reflection (such as water), a so-called memory effect can result: The measured signal of the lower reflecting area may be up to four grey values too high and the detectors need a certain amount of time (in TM for example up to 1000 pixels) until they are normalised again. This effect leads to a local banding of up to 16 lines [28, 48].

The memory effect also appears, to a very small degree, in the data used at the edge of clouds, snow and water. Its influence on the grey values is, however, too small to cause classification errors, and therefore no correction is necessary for operational use.

Within the framework of the project, the memory effect was not corrected in any of the data sets.

3.2 Geometrical correction

3.2.1 Overview

By geometrical correction, remote sensing data is projected orthogonally onto a horizontal reference level [6]. The importance of geometrical correction has greatly increased in recent years. The following factors are responsible for this [57]:

- the growing complexity of remote sensing systems (e.g. adjustable mirrors, different spatial resolution),
- the growing interest in multisensor image processing,
- the growing demand for precision, timely resolution and repeatability of remote sensing measurements.

Geometrical correction is gaining in importance due to more frequently combined multitemporal and multisensor evaluations.

Various terms are used to describe the geometric correction of imagery [57]:

- *Registration*
  The alignment of one image to another image of the same area.
- *Rectification or georeferencing*
  The alignment of an image to a map.
- *Geocoding*
  A special case of rectification that includes scaling to a uniform pixel size. This permits convenient analysis of images from different sources in a GIS.
- *Orthorectification*
  Correction of the image for relief-induced distortions in order that the image is presented in an orthographic projection.

The influence of ground elevation on the accuracy of geometrical correction was already shown in various reports [38, 64]. In multitemporal scenes covering middle and high latitudes, this aspect acquires additional significance. In these areas, images of different tracks are often used. The consequence of this complementary view of the terrain occasionally leads to parallaxes of more than a pixel, even for small topographic variations. Due to the resulting mixed signatures, a multitemporal evaluation would be severely impeded. In the land use statistics project, highly accurate orthorectification of the satellite data was striven for from the beginning.

There are two approaches for the geometrical correction of images:

- parametrical approach,
- empirical (non-parametrical) approach.

The parametrical method attempts to describe the image capture situation based on the collinearity of image and object lines. In addition to the parameters of outer orientation (roll, pitch, yaw, coordinates of the projection centre), special sensor parameters can also have an influence [24]. Parametrical procedures are especially useful for orthorectification of scenes in low contrast or cartographically badly documented areas. However, the necessary parameters for an exact adjustment can not be delivered by satellite operators or can only be provided with insufficient precision and temporal resolution [9]. They usually have to be estimated with the help of a few ground control points [27, 34, 63].

In the empirical procedure, the geometrical conditions are recorded, without knowing the imaging process. In the process a numeric transformation of the image data onto the reference geometry is determined using ground control points [24]. Amongst the most important transformations are the Helmert transformation, the affine transformation and transformations with polynomials of the second and third order. The affine transformation is preferred in practice. The internal image geometry is thereby not distorted and it allows the introduction of different scales and rotation angles in the x and y directions. Local distortion in the original image can therefore be reduced. This method is easy to use and can be operated independently of the sensors used. The empirical approach is especially suitable for satellite images since the flight path is relatively stable and topographic variations are small in relation to the satellite orbit altitude [41]. The empirical procedure also allows for improved accuracy if the ground elevation is taken into account [38].

Within the framework of the land use statistics project, the empirical orthorectification as well as the parametrical orthorectification were examined. The theoretical basis and the practical implementation are given below. In conclusion, the results achieved will be evaluated.

3.2.2 Determination of ground control points

Ground control points are needed for the determination of unknown parameters in geometrical correction. Their accuracy decisively influences the quality of orthorectification; therefore the effort required for their determination has to be adjusted to the required accuracy. Ground control points should have the following characteristics:

- small feature size,
- high contrast in image data,
- no generalization in the map,
- temporally as stable as possible.

For TM and XS data the following objects proved to be suitable:

- intersections of class 4 or 5 roads,
- bridges,
- detached buildings.

The image coordinates of the ground control points were determined on the screen based on a false-colour IR representation (NIR/red/green as RGB). The determination of map coordinates can be achieved in various ways according to the information basis. The most common information sources include:

- maps in analogue format,
- orthorectified digital images or maps,
- orthorectified digital vectors,
- ground control point data base.

In the land use statistics project, the map coordinates and ground elevation of all ground control points were determined using the topographic map of 1:25'000 scale. In order to read the coordinates, a special magnifying ruler was used.

During determination of the ground control points, the following inaccuracies can occur:

- inaccurate determination of image coordinates,
- inaccurate determination of map coordinates,
- inaccurate determination of terrain elevation,
- non-linear local distortions in image,
- inaccurate map basis (e.g. through generalisation).

These inaccuracies usually lead to high residues of the ground control points and have to be resolved. Errors in the determination of image coordinates, map coordinates and terrain elevation can be corrected. In the case of non-linear distortions and inaccurate map basis the exclusion of the affected ground control points from the model calculation is suggested [46].

3.2.3 Resampling

In geometrical correction, the position of the pixels in the uncorrected image corresponding to the pixels in the corrected image is calculated (backward transformation). For this calculation, the parameters of the geometrical model are used. The image coordinates resulting from the transformation usually do not hit exactly the centre of a pixel. In the orthorectification process, a resampling is therefore absolutely necessary. The resampling procedures used most commonly in remote sensing are [57]:

- nearest neighbour,
- bilinear interpolation,
- cubic convolution.

It is controversial as to which of these conventional resampling procedures is the most suitable for a subsequent digital classification. Itten [35] prefers the nearest neighbour procedure, because no new, artificial digital numbers are created in the orthorectified image. Dikshit et al. [21] achieved the best classification results in an empirical research with the help of bilinear interpolation. Pratt [52] finally points out that the two-dimensional sensitivity variability of the sensor detectors can be best adjusted using the cubic convolution procedure.

Based on the research of Dikshit et al. [21] and our own tests, bilinear interpolation is recommended for classification purposes.

3.2.4 Empirical orthorectification

The empirical orthorectification carried out within the framework of the project was originally developed by Bitter [7] for optical satellite data. Kellenberger [37] developed this procedure further by additionally taking the curvature of the earth into account.

The procedure is based on an affine transformation. This linear equation has six variables and can carry out translations, rotations and scale changes independent of the x- and y-direction. The terrain-induced distortion is corrected through the transfer of the central perspective line information in an orthogonal projection with the help of a correction vector. This happens with all ground control points, so that the calculation of the transformation coefficient will not be negatively influenced by terrain distortion. This correction vector is also used with the actual transformation of each individual image element.

For this procedure the following parameters are necessary:

- radius of the earth,
- satellite orbit altitude,
- viewing angle,
- IFOV,
- pixel coordinates of the nadir line.

Table 4 provides an overview of the empirical orthorectifications carried out within the framework of the project. The residues should not be used as a measure of accuracy of the geometric correction.

Table 4: Overview of the orthorectifications carried out

Date	Sensor	Research area	Ground control points		Mean RMSE [m]		Elevation model	Resampling
			defined	used	in x	in y		
09.08.90	TM	Yverdon	77	51	10.0	9.3	DHM25	nearest neighbour, 25 m
30.06.91	Pan	Zug, Rigi, Beckenried	130	85	4.0	4.5	DHM25	nearest neighbour, 10 m
30.06.91	XS	Zug, Rigi, Beckenried	90	72	7.0	7.6	DHM25	nearest neighbour, 10 m
11.07.91	TM	Zug, Rigi, Beckenried	190	130	8.6	6.7	DHM25	nearest neighbour, 10 m

Ehrler [25] checked the positional accuracy of the empirical orthorectification by means of a GIS approach. For the TM scene of 11.07.91, this resulted in an average positional error of approximately 12 m, and for the Pan and XS scenes of 30.06.91, an average positional error of 6 m [25].

In summary, it can be stated that with the empirical orthorectification the requirements of the Swiss land use statistics can be met. A disadvantage of the method is the necessity of a large number of ground control points, especially since their determination is very time-consuming. In addition, a good spatial distribution of the ground control points in the area can not always be ensured.

3.2.5 Parametrical orthorectification

The parametrical orthorectification used was originally developed by Toutin for SPOT HRV [30, 63] and was tested later for Landsat TM [50], for MOS MESSR and Seasat SAR [65] as well as for airborne SAR-systems [66]. The procedure can be used for different sensors, because it is based on the collinearity principle and takes into account the different distortions relative to the global geometry of the collected image. These are the following [67]:

- distortions relative to the platform (position, velocity, orientation),
- distortions relative to the sensor (viewing angle, IFOV, detector signal integration time),
- distortions relative to earth (geoid-ellipsoid including ground elevation),
- distortions relative to the cartographic projection (ellipsoid-cartographic plane).

Attitude and orbit data as well as some ground control points form the prerequisites of this model. The attitude data for each line include the change of angular speed along the three axes in relation to ground. The orbit data define the geometrical parameters of the sensor and its platform. For SPOT HRV, for example, these are [67]:

- instantaneous field of view (IFOV),
- viewing angle,
- detector signal integration time,
- radial velocity,
- angular speed,
- distance between earth centre and satellite platform,
- satellite orbit altitude,
- orbital inclination,
- ascending node longitude,
- satellite argument,
- pixel coordinates of the image centre,
- geographic coordinates of the image centre.

In general, the attitude and orbit data necessary for the orthorectification are read directly from the header data of the data carrier (CD or magnetic tape) [51]. Sometimes the orbit information in the header of the data carrier are, however, defective or incomplete and have to be corrected with the help of corresponding nominal values [45]. Even if orbit data is not available, the use of nominal values seems to be unproblematic.

Table 5 presents the parametrical orthorectifications carried out within the framework of the project. In comparison to the empirical approach, the residues are a good indicator of the accuracy of the geometric correction.

Table 5: Overview of the parametric orthorectifications carried out

Date	Sensor	Research area	Ground control points		Mean RMSE [m]		Elevation model	Resampling
			defined	used	in x	in y		
08.04.95	TM	Yverdon	79	65	8.9	9.4	DHM25	bilinear, 25 m
03.05.95	TM	Yverdon	76	63	9.6	5.7	DHM25	bilinear, 25 m
20.06.95	TM	Yverdon	82	65	10.6	6.7	DHM25	bilinear, 25 m
22.07.95	TM	Yverdon	105	82	9.8	8.1	DHM25	bilinear, 25 m
14.08.95	TM	Yverdon	65	60	10.5	5.6	DHM25	bilinear, 25 m
24.09.95	TM	Yverdon	74	60	7.9	9.0	DHM25	bilinear, 25 m
17.10.95	TM	Yverdon	76	64	11.5	8.9	DHM25	bilinear, 25 m
19.07.95	XS	Yverdon	96	87	6.3	5.5	DHM25	bilinear, 25 m
17.10.95	XS	Yverdon	76	62	5.9	5.6	DHM25	bilinear, 25 m

The average RMSE of the used ground control points in the seven TM scenes range from 0.4 to 0.5 pixels, in the two XS scenes it is 0.4 pixel. In addition, an overlay of digitized field borders showed that a systematic deviation could be localised neither in TM nor in XS data. However, in TM data the column duplications led to visible local distortions [46].

Parametrical orthorectification thereby fulfils the requests of the Swiss land use statistics in relation to geometrical accuracy. A special advantage is that the method already leads to subpixel accuracy with only eight to ten ground control points. This way, the time necessary for the determination of the ground control points can be reduced compared to the empirical approach. Based on this, the parametrical approach is preferred to the empirical approach.

3.3 Radiometric correction

3.3.1 Overview

Satellite data from different sensors and different acquisition times can not be directly compared with each other. Amongst other things, they are influenced by sensor calibration, the position of the sun, as well as by atmospheric and topographic effects. With the help of radiometric correction, the object-specific influences can be reduced and at the same time the data can be transformed into comparable physical units. This is referred to as radiometric calibration [57] which makes it possible to a certain point that the satellite data is reduced to its object-specific reflective properties.

There are several levels of radiometric correction (Figure 5, p. 36).

The first converts the reflectance values registered by the sensor to at-sensor radiances and requires sensor calibration information.

The second is the transformation of at-sensor radiances to radiances at the earth's surface. This level is much more difficult to achieve, since it requires information about the atmospheric conditions at the time and location of the image. During operational use, the availability of this information can not always be counted on.

Figure 7 right top:

Degrees of forest mixture in the Beckenried research area

Legend:
1: Deciduous forest (light green)
2: Mixed forest (green)
3: Coniferous forest (dark green)
0: Non-forest (white)

Figure 8 right bottom:

Land use I in the research area of Yverdon (monotemporal)

Legend:
1: Deciduous forest (light green)
2: Mixed forest (green)
3: Coniferous forest (dark green)
4: Industrial areas (violet)
5: Buildings (red)
6: Vineyards (pink)
7: Agricultural areas 1 (light yellow)
8: Agricultural areas 2 (dark yellow)
9: Agricultural areas 3 (light brown)
10: Agricultural areas 4 (dark brown)
11: Alpine agricultural areas (beige)
12: Lakes (blue)
0: Null category (white)

Figure 4 on the centrefold, left:

Quicklooks of Landsat TM und SPOT satellite scenes used in the project

(The SPOT Pan scene of 30–06–91 is not reproduced, because there is the SPOT XS scene from the same place and date). All the scenes are reproduced at a comparable scale. That is why the scenes have different sizes: a Landsat TM full scene covers about 185x185km², a Landsat TM quarter scene 95x95km² and a SPOT scene 60x60km².

Left side:	top	Landsat TM 195 / 027	full scene from 9–8–1990
	middle right	SPOT XS 054 / 255	full scene from 30–6–1991
	bottom	Landsat TM 195 / 027	full scene from 11–7–1991

Abbildung 7: Waldmischungsgrad
Figure 7: Degrees of forest mixture

Beckenried

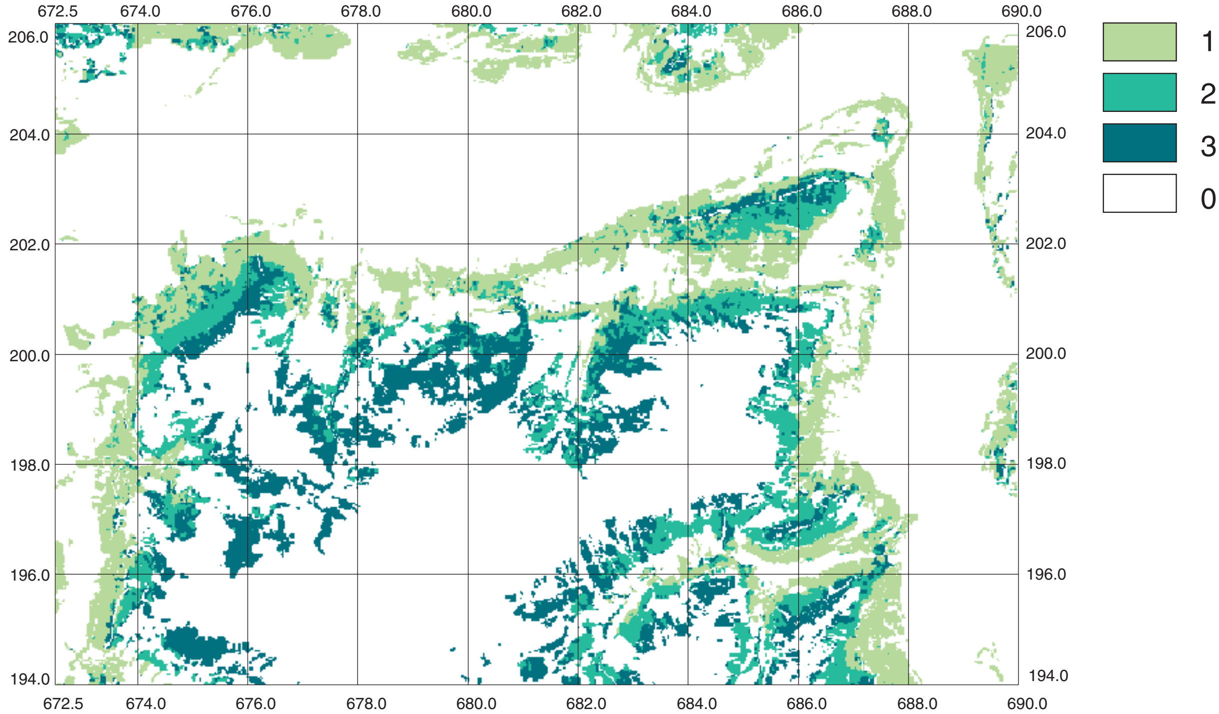


Abbildung 8: Landnutzung I
Figure 8: Land use I

Yverdon

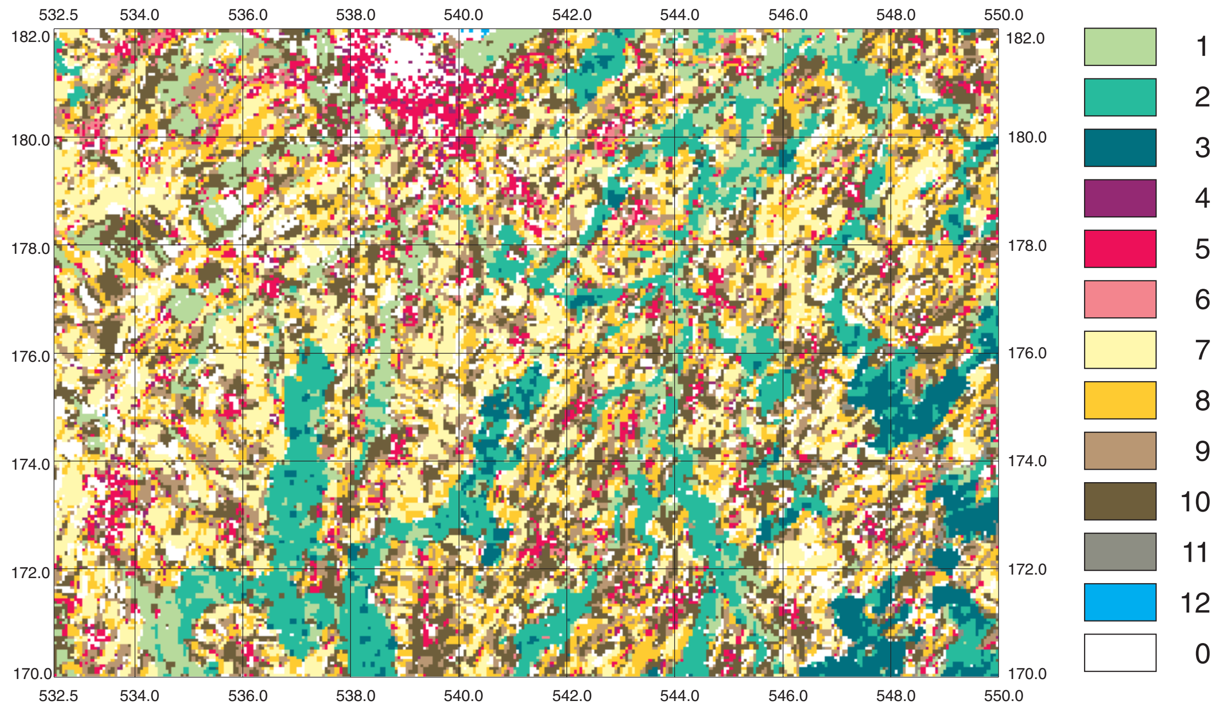
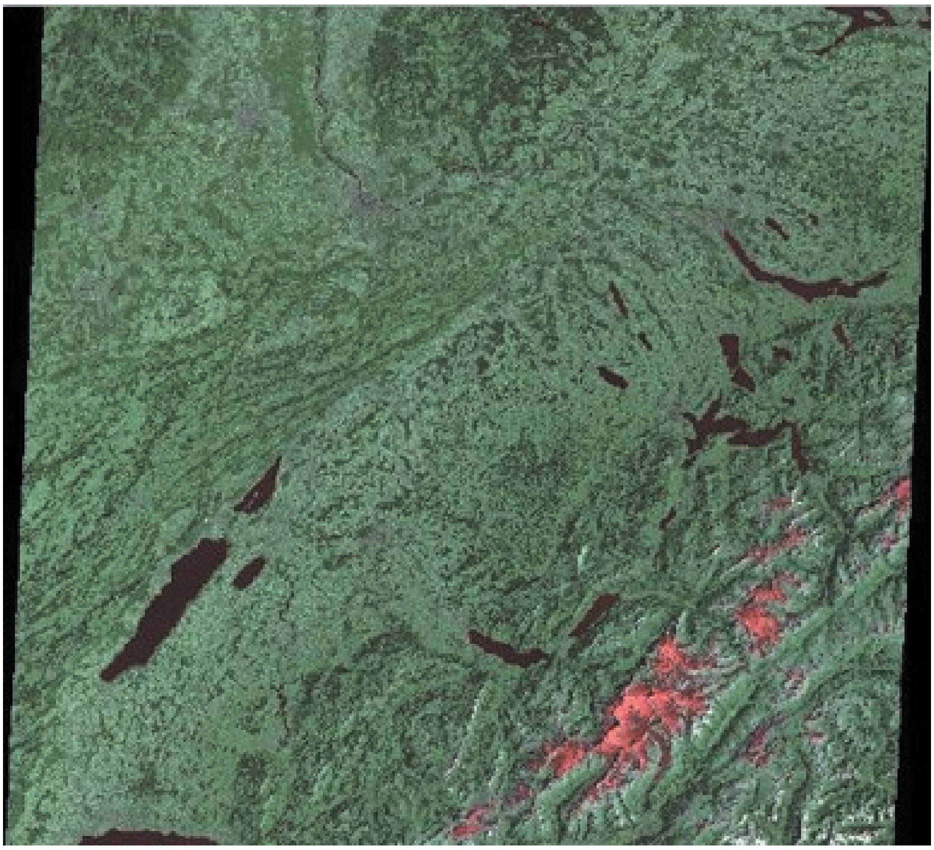
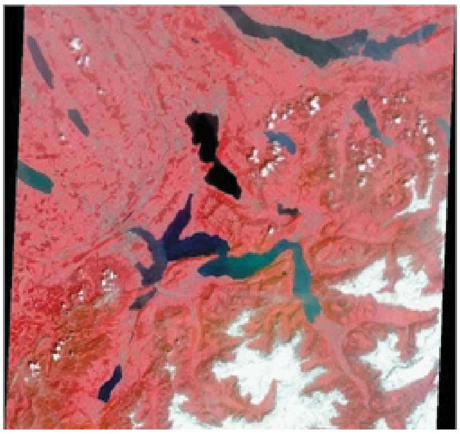


Abbildung 4: 'Quicklooks' der im Rahmen des Projekts verwendeten Landsat-TM und SPOT-Satellitenszenen

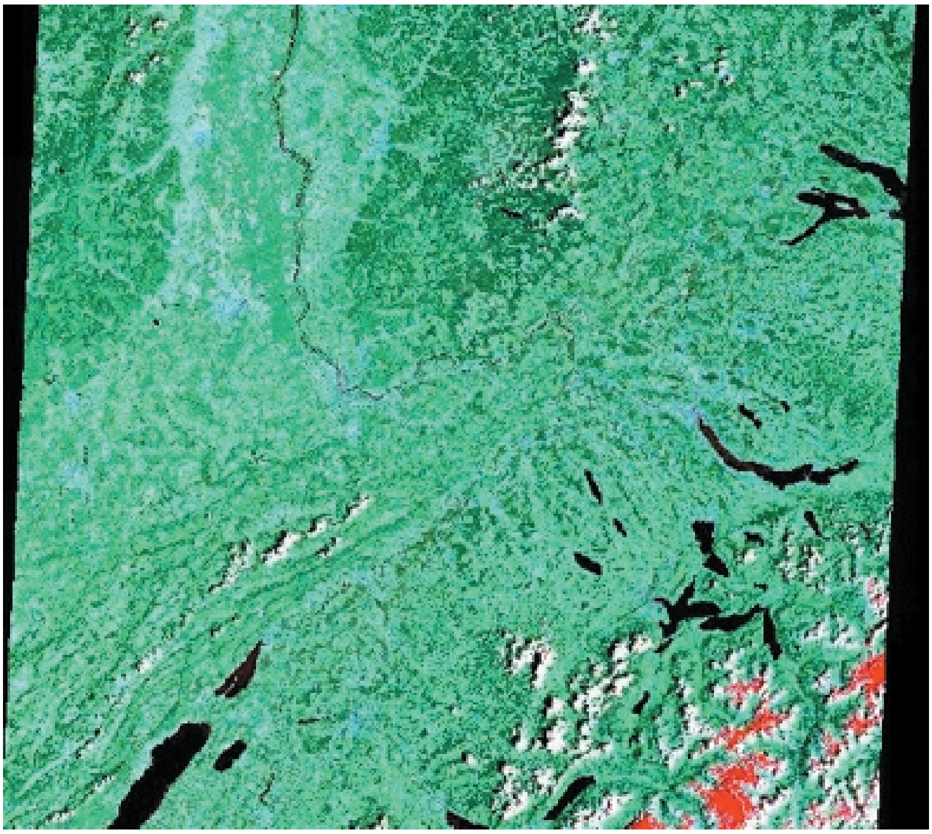
Figure 4: Quicklooks of Landsat TM and SPOT satellite scenes used in the project



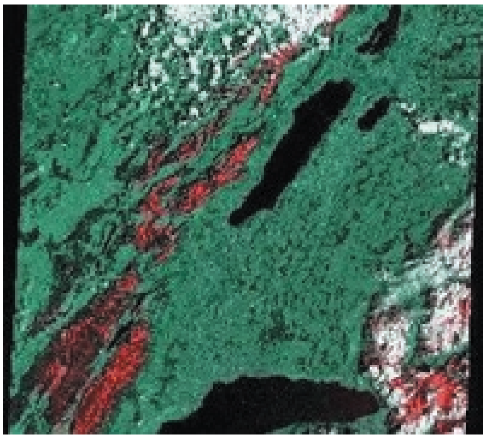
Landsat TM
195/027
9–8–1990



SPOT
054/255
30–6–1991

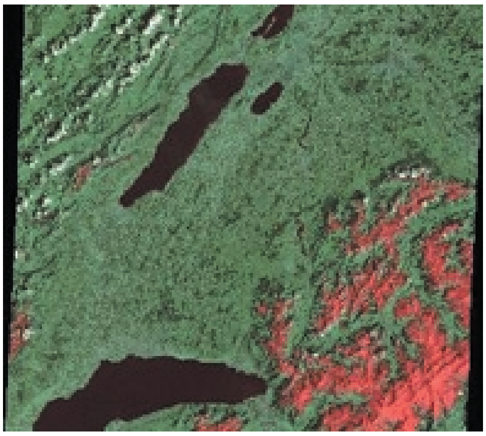


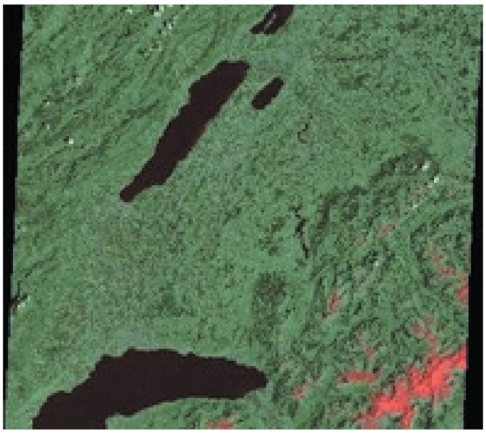
Landsat TM
195/027
11–7–1991



Landsat TM
196/027 SE
8–4–1995

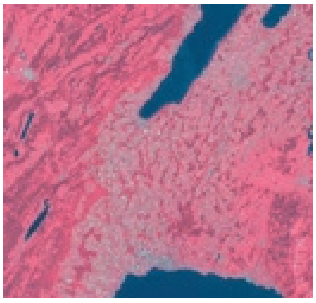
Landsat TM
195/027 SW
3–5–1995



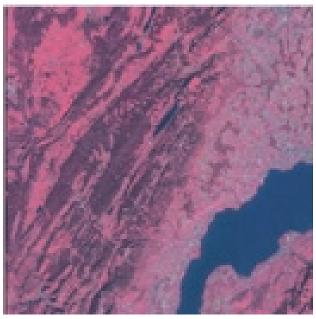


Landsat TM
195/027 SW
20–6–1995

Landsat TM
195/027 SW
22–7–1995

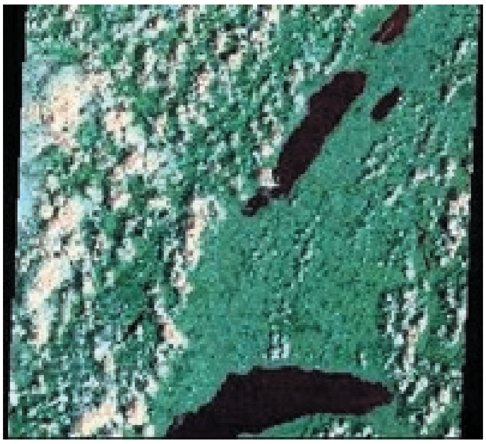


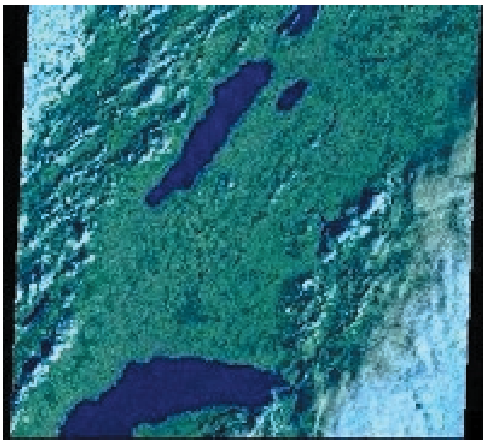
SPOT
050/255
19–7–1995



SPOT
050/255
17–10–1995

Landsat TM
196/027 SE
14–8–1995





Landsat TM
195/027 SW
24–9–1995

Landsat TM
196/027 SE
17–10–1995

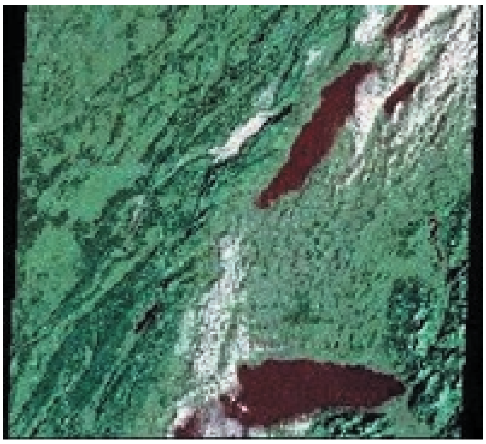


Abbildung 9: Landnutzung II
Figure 9: Land use II

Yverdon

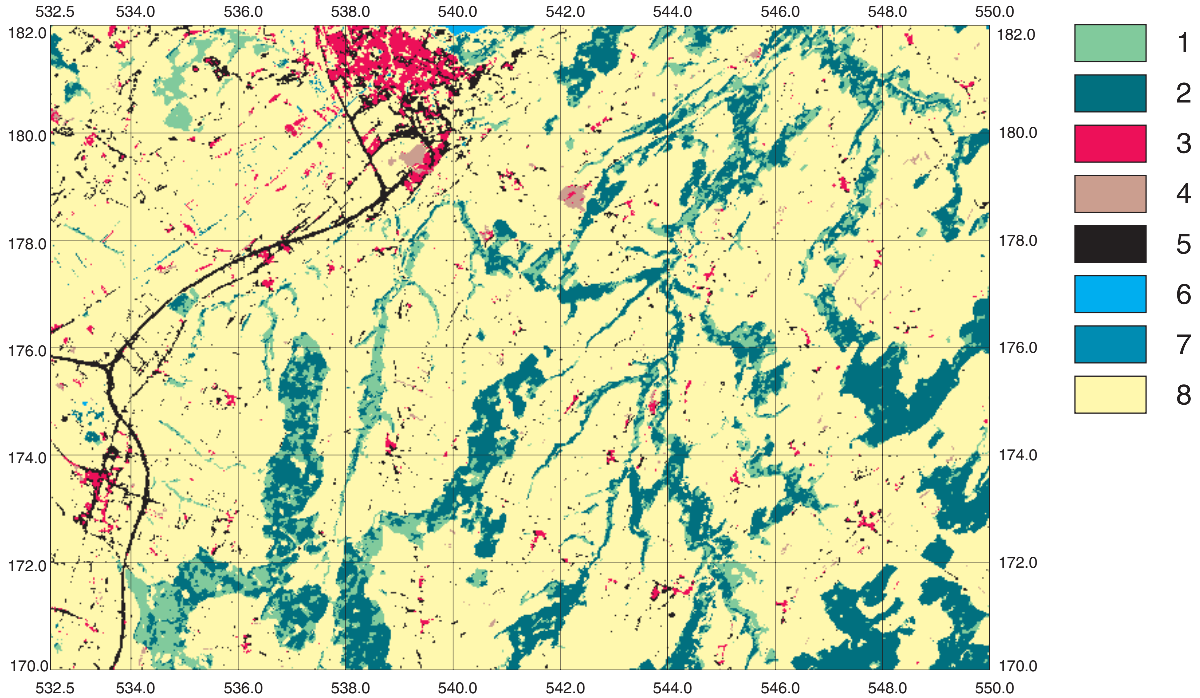


Abbildung 10: Landwirtschaftliche Kulturen
Figure 10: Agricultural cultivation

Yverdon

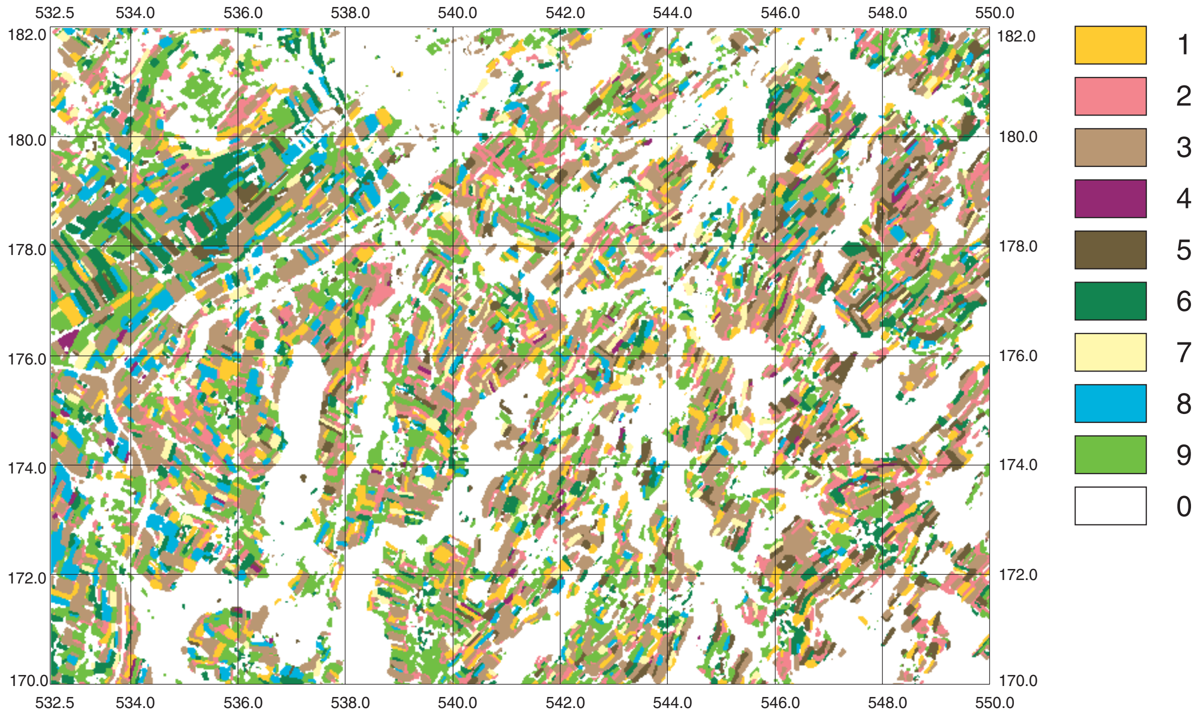


Figure 9 left top:

Land use II in the research area of Yverdon (multitemporal)

Legend: 1: Deciduous forest (green)
2: Coniferous forest (dark green)
3: Settlement and urban areas (red)
4: Construction sites, bare land (maroon)
5: Transportation areas (black)
6: Lakes (blue)
7: Rivers (dark blue)
8: Agricultural areas (yellowish)

Figure 10 left bottom:

Agricultural cultivation in the research area of Yverdon

Legend: 1: Barley (dark yellow)
2: Rye (pink)
3: Wheat (light brown)
4: Peas (violet)
5: Potatoes (brown)
6: Maize (dark green)
7: Rapeseed (yellowish)
8: Sugar beets (blue)
9: Meadow (light green)
0: Others (white)

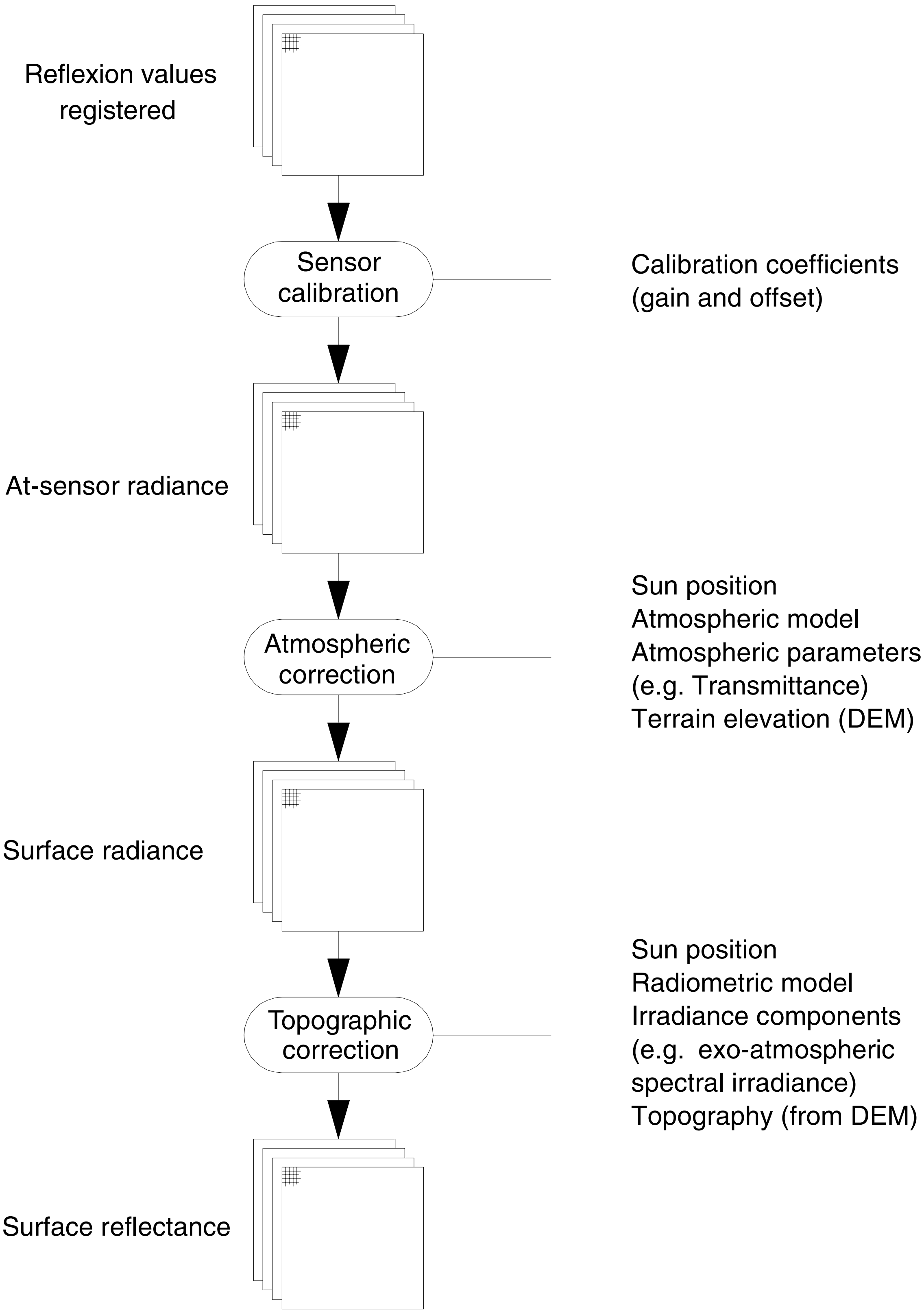
Figure 4 on the centrefold, right:

Quicklooks of Landsat TM und SPOT satellite scenes used in the project

Right side: From top left to bottom right:

Row 1 left	Landsat TM 196 / 027	quarter scene from 8–4–1995
Row 1 right	Landsat TM 195 / 027	quarter scene from 3–5–1995
Row 2 left	Landsat TM 195 / 027	quarter scene from 20–6–1995
Row 2 right	Landsat TM 195 / 027	quarter scene from 22–7–1995
Row 3 left	SPOT XS 050 / 255	full scene from 19–7–1995
Row 3 middle	SPOT XS 050 / 255	full scene from 17–10–1995
Row 3 right	Landsat TM 196 / 027	quarter scene from 14–8–1995
Row 4 left	Landsat TM 195 / 027	quarter scene from 24–9–1995
Row 4 right	Landsat TM 196 / 027	quarter scene from 17–10–1995

Figure 5: Data flow for the radiometric correction of remote sensing data.
They contain the transformation of the measurements into physical units.
Source: [57], modified.



A common technique for atmospheric correction uses a “dark object” in the image as calibration target [1, 15]. It is assumed that the dark object has uniformly zero reflectance for all bands and that any non-zero measured radiance must be due to atmospheric scattering. To reduce these effects, grey values of dark objects of all pixels are subtracted in the respective band (dark object subtraction). The problem with this method is the determination of suitable dark objects in the image as well as in the assumption that their reflectance equals zero. In addition, path transmittance is neglected in this approach, which is important above all in the NIR and SWIR range.

More recent studies use the estimation of radiance of dark objects in combination with a radiation transfer model (e.g. Modtran [5] or 6S [69]). With the help of dark objects, the modelling of the atmosphere can be calibrated [16, 62]. Since no atmospheric measurements are needed, operational use of this approach is feasible. But again, the determination of dark objects can be difficult in practice. This problem is avoided by Richter [53] by using any invariant reference objects in an image for the calibration of the radiation transfer model.

Finally, in the third level, object-specific surface reflectance is determined with the help of surface radiance. In areas with distinctive terrain, the varying illumination significantly influences the surface radiance. The influence of topography can be adjusted and reduced using an elevation model.

An atmosphere model to take into consideration atmospheric influences may additionally be included to expand this slope-aspect correction [72]. The inclusion of diffuse sky radiance with help of the sky view factor as well as of the terrain view factor can furthermore improve this correction [23].

In the following section both methods used in the framework of the project will be discussed. The theoretical basis and the practical completion will be explained and the achieved results evaluated.

3.3.2 Semi-empirical radiometric correction

Semi-empirical c-correction deals with an object-specific illumination correction, as introduced by Teillet [61]. Thereby, all image elements are treated as if they all show the illumination behaviour of the selected corrected category. The method makes allowances for the portion of incident radiation by means of the cosine of the angle of solar incidence. The objects are regarded as lambertian emitters. This adjustment will be supplemented with a factor c, which takes the diffuse sky radiation into consideration. The factor c is the result of the linear correlation between the grey values measured by the sensor and the angle of solar incidence.

In Table 6 the semi-empirical radiometric corrections carried out within the framework of the project are listed.

Table 6: Overview of the semi-empirical radiometric corrections carried out

Date	Sensor	Research area	Elevation model	Category of correction
30.06.91	XS	Beckenried	DHM25	Swiss land use statistics, vegetation
30.06.91	Pan	Beckenried	DHM25	Swiss land use statistics, vegetation
11.07.91	TM	Beckenried	DHM25	Swiss land use statistics, vegetation

The advantage of semi-empirical radiometric correction was examined with a maximum likelihood classification of six different types of vegetation in the Beckenried research area. After the correction, there was a deterioration of classification accuracy in HRV as well as in TM data of over 2% [42]. These results contradict the experience with c-correction in connection with forest classification. By using this method, an improvement in classification accuracy of between 2% and 6%, depending upon the research area, was achieved.

The results show that semi-empirical radiometric correction in land use classification does not necessarily lead to an improvement in accuracy. The use of this procedure is only recommended for the classification of special categories (e.g. in the differentiation between forest/ non-forest).

3.3.3 Physically-based radiometric correction

In the framework of the project, physically-based radiometric correction suggested by Sandmeier [55] was used. This procedure considers both atmospheric as well as topographic effects.

In this procedure the following simplifying assumptions were made:

- The atmosphere is homogenous in the horizontal direction. Variations appear only in the vertical direction.
- Aerosol optical depth is homogenous in the vertical direction. Terrain induced variations of aerosol concentration are thereby not considered.
- Land cover is unknown. Therefore a lambertian reflection characteristic of land cover will generally be assumed. An object-specific BRDF will thus not be considered.
- All image pixels are considered as nadir pixels, whereby the length of the beam path for all pixels is the same. The FOV as well as the viewing angle of a sensor are not considered.
- A uniform ground reflectance of type “green vegetation” is assumed.

In order to calculate the atmospheric parameters for horizontal surfaces necessary for the correction, the radiation transfer model 6S was used [69]. In case no suitable measurements (radio sonde measurements, meteorological observations) are available, certain input parameters can be approximated with the help of predefined standard models. This concerns the atmospheric conditions, the aerosol type and the spectral variation of ground reflectance. With the help of aerosol models certain aerosol types can be estimated. For the determination of the aerosol concentration, however, the optical depth (μ_{meteo}) is additionally needed.

Table 7 gives an overview of the physically-based radiometric corrections carried out within the framework of the project.

In the Beckenried research area the use of physically-based radiometric correction was tested with the help of TM data in a classification of the degree of forest mixture. In a parallelepiped classification, an improvement in classification accuracy of 5% was achieved, with the minimum distance method 2% and in a probability-based classification 7%. In the maximum likelihood method, the classification accuracy deteriorated by 1% [43].

Table 7: Overview of the physically-based radiometric corrections carried out

Date	Sensor	Research area	Atmospheric model	Aerosol model	μ_{meteo} [km]	Ground reflection	Elevation model
09.08.90	TM	Yverdon	radiosonde measurements	continental	15-40	green vegetation	DHM25
11.07.91	TM	Beckenried	radiosonde measurements	continental	12-40	green vegetation	DHM25
08.04.95	TM	Yverdon	US standard 62	urban	40	green vegetation	DHM25
03.05.95	TM	Yverdon	Midlatitude summer	continental	26	green vegetation	DHM25
20.06.95	TM	Yverdon	Midlatitude summer	continental	39	green vegetation	DHM25
22.07.95	TM	Yverdon	Midlatitude summer	continental	11	green vegetation	DHM25
14.08.95	TM	Yverdon	Midlatitude summer	urban	17	green vegetation	DHM25
24.09.95	TM	Yverdon	US standard 62	continental	20	green vegetation	DHM25
17.10.95	TM	Yverdon	US standard 62	urban	10	green vegetation	DHM25
30.06.91	Pan	Beckenried	radio sonde measurements	continental	18-40	green vegetation	DHM25
30.06.91	XS	Beckenried	radio sonde measurements	continental	18-40	green vegetation	DHM25
19.07.95	XS	Yverdon	Midlatitude summer	continental	40	green vegetation	DHM25
17.10.95	XS	Yverdon	US standard 62	urban	8	green vegetation	DHM25

In the Yverdon research area, the physically-based radiometric correction achieved an improvement in accuracy of almost 5% [45] in a classification of various agricultural areas, using a maximum likelihood classification with TM data. This is all the more surprising, since the agricultural areas are limited in their elevation extent as well as in their slope.

Through the physically-based correction some obvious errors can appear at the ridges and in weakly illuminated areas. These features, already observed by Sandmeier [55], can be the consequence of insufficient determination of the angle of incidence of the solar and shadow areas. These errors could, under certain circumstances, be avoided through a higher resoluted DEM. Apart from that, the neglect of neighbourhood effects can lead to artefacts.

In view of these results, physically-based radiometric correction is recommended for general land use classification.

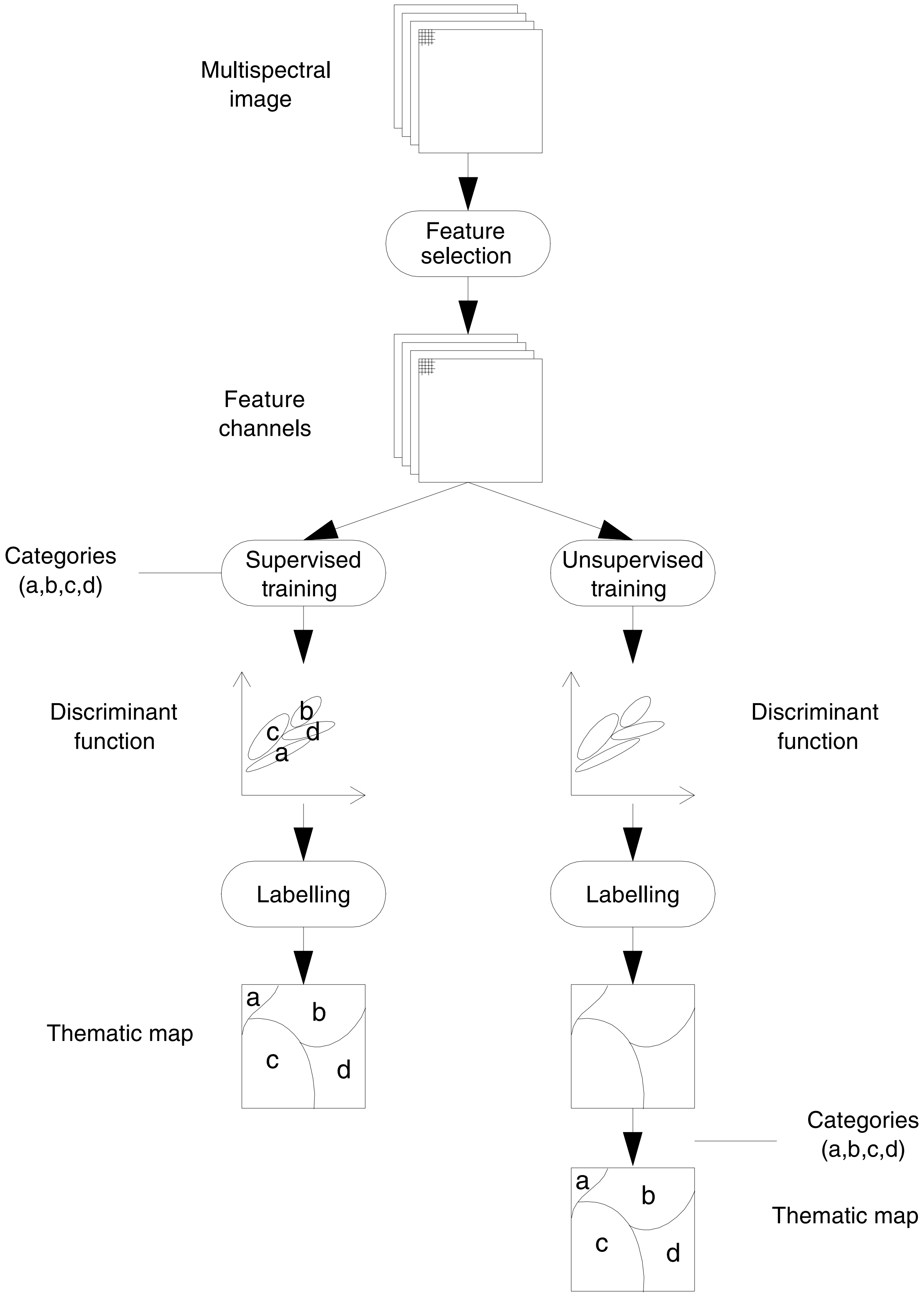
3.4 Classification

3.4.1 Overview

Image classification is the process to extract thematic information from image data whereby the allocation of a pixel to a category is central. This assumes that the categories are distinguishable in the image data. A number of factors can cause confusion among the signatures, including sensor and scene-related radiometric interference effects, and class mixing within a pixel.

Traditionally, thematic classification involves three fundamental steps (Figure 6).

Figure 6: Data flow of classification of remote sensing data



Feature extraction aims to reduce the image data to the significant feature parameters to enable the classification of the imaged area. The multispectral image data can be used directly in classification, but the different spectral bands are often highly correlated, resulting in an inefficient analysis. Furthermore, image-derived features (e.g. spatial texture) may provide more useful information for classification.

Within the framework of training, representative samples of each category, known as training samples or simply training areas, are defined which can be used to determine a discriminant function in the feature area. If the training areas are labelled to categories with the help of ground truth, this is known as supervised training. Otherwise the algorithm assumes a priori that differences in the data are present. This is then an unsupervised training.

Finally, when labelling is carried out, the discrimination function is applied to the entire feature image. During a supervised training, the labels are associated with the discriminant function, whereas an unsupervised training requires an analyst to carry out the labelling later on.

The procedures examined or used within the framework of the land use statistics for feature extraction, training or labelling are presented below.

3.4.2 Classification assessment, classification accuracy

Digital classifications are often verified with the help of ground truth data. The classification accuracy can be presented using an error matrix. This table contains the number of observations (usually pixels) allocated to a certain category during classification in relation to the categories of the ground truth. The columns usually represent the reference data, while the classification categories are shown in the lines. Ideally in an error-free classification, all elements not lying within the main diagonal of the error matrix would equal to zero. The advantage of an error matrix is that a type 1 error, a commission error, as well as type 2 error, an omission error, are presented.

The error matrix is the starting point for a whole range of descriptive and analytical statistical techniques for classification assessment. Congalton [17] provides an overview. The simplest descriptive measure is the overall accuracy, defined as the percentage of correctly classified pixels.

In the following chapters, the classification results are assessed using the overall accuracy. Since the comparison of the classification results and the ground truth data occurs pixel-to-pixel, geometric inaccuracies (including those of the ground truth data) are equally counted as classification errors. Therefore, real classification accuracy may always lie somewhat higher.

3.4.3 Determination of non-classifiable or missing areas

Satellite data always contain areas that can not be analysed. With optical sensors this is mostly due to cloud cover and cloud shadows. Depending on the task, snow-covered areas must also be included.

The determination of non-classifiable areas can take place in two ways:

- automatic,
- manual.

Automatic determination, for example, is based on the classification of the spectral information in the satellite image. The procedure corresponds to that of the classification process, as described below for land use classification. However, this method leads to errors for cloud shadows.

During manual delineation using a suitable band combination, the missing area is vectorised on the screen and then rasterised. This procedure has the advantage that the interpreter is able to take into account knowledge of local conditions during delineation.

For the satellite data evaluated in the land use statistics project, analysis of missing areas always took place with the help of manual vectorisation on the screen.

3.4.4 Relief information as additional classification feature

Conventional classification procedures make exclusive use of spectral satellite image information. There are, however, other sources of information that can be used for the identification of land use and so can influence the classification process. The following examples shows this:

- At 1500 m altitude, “favourable alpine pastures” are more likely than “favourable arable land and meadows”.
- Vineyards are more likely on south-facing slopes than on slopes exposed to the north.
- Meadows are more likely in areas of low slope than in areas of steep slope.

Within the framework of the project, various tests for the integration of terrain information into the classification process were carried out. In the Beckenried research area the terrain elevation, together with the TM and XS data, was used for a probability-based classification of the degree of forest mixture (deciduous, mixed and coniferous forest). This resulted in a classification improvement of 5% to 12% compared to a conventional maximum likelihood classification without terrain information [43].

In the Yverdon research area, land use classification was carried out using TM data. Terrain elevation was additionally used to better differentiate the degree of forest mixture. Terrain elevation and aspect were used to better differentiate the agricultural areas. The result of this probability-based classification was finally aggregated into seven categories and compared with the Swiss land use statistics. The comparison showed that the addition of terrain information led to an improvement of more than 5% as compared to a maximum likelihood classification without terrain information [43].

In the Yverdon research area terrain elevation, aspect and slope were used together with TM data for the differentiation of nine different land use categories. There was a resulting improvement in classification of 10% [44].

These results show that additional terrain information achieves significant improvements for the classification of certain categories. The use of terrain information as an additional feature of classification is therefore recommended.

3.4.5 Texture information as additional classification feature

Texture is an important feature for identifying objects in an image. In contrast to spectral information, texture comprises the spatial distribution of grey value variation in the bands. Information on homogeneity, contrast and linear structures can be determined with the appropriate texture parameters.

The textural information is often presented in the form of grey-level co-occurrence matrices. According to Haralick et al. [33], grey-level co-occurrence (GLC) matrices are used for the derivation of second-order statistics in digital images. A GLC matrix is the estimation of the probability of the transition from a grey value i to a grey value j of two neighbouring image elements, where the neighbourhood is defined by a transition vector. The estimation results from the registration of the grey value transitions and accompanying normalisation. A GLC matrix therefore comprises the normalised frequency p_{ij}, with which two neighbouring image elements at a defined distance d, with the grey values i and j respectively, appear in the image in a certain direction. The sequence of the grey values is not considered; it is therefore a symmetrical matrix.

Observation of the GLC matrix allows an initial interpretation: the more the activated elements gather around the diagonal, the more homogeneous is the picture. In contrast, elements far away from the diagonal indicate strong grey value jumps, and thus indicate inhomogeneity.

So that the complete GLC matrix does not have to be used for the description of texture, so-called texture features are derived from the GLC matrices. They present the characteristics of the GLC matrix in a single value.

Within the framework of the project, two texture measures were tested in regard to their suitability for classification: homogeneity and angular second moment [57]. Both texture measures were computed for the Yverdon research area using a 3×3 window size in a horizontal and a vertical direction. Band 3 of the XS scene from 19.7.1995 served as the basis. With the help of a neural network, nine different land use categories were differentiated. The addition of the four texture bands resulted in an improvement in classification of more than 4% [22].

This test shows that the textural information can bring a significant improvement in classification. Producing these additional features is quick and easy. Their use during operational land use classification is therefore recommended.

3.4.6 One-dimensional separability for the feature selection

One-dimensional separability is a measure for the separability of two categories [42]. It is calculated on the basis of the difference of two frequency distributions in a certain band. To calculate this measure no particular statistical distribution is assumed.

The maximum one-dimensional separability can be calculated for all category pairs. With the help of the resulting separability matrix, those categories can be determined which can only be insufficiently separated by the available features. These categories should be aggregated prior to a classification.

The features with the highest one-dimensional separability can also be summarised in a feature matrix. It gives an indication of the optimal features for classification.

The method of maximum one-dimensional separability has the advantage that no assumption on the frequency distribution has to be made for the examined categories. In particular, categories with a non-gaussian frequency distribution (e.g. terrain information) can be analysed. The disadvantage of the method is that only one band can be included in the calculations. Even if only one band for the appropriate separability is selected, additional bands would improve the multispectral classification.

The method is effective when only one or two features are available for classification. However, since multispectral data are often used for classification, this method is rarely used.

3.4.7 Jeffries-Matusita distance (JMD) for the feature selection

JMD is a measurement of statistical separability and is defined as the mean difference between the probability density functions of two categories [57]. Any band combination can be analysed in the process. This measurement can be used to select the ideal feature combination for the classification.

JMD can be calculated separately for each category pair. For a total assessment, the average and minimal JMD of each pair can be included. The average distance describes the general separability of the categories, while the minimal distance refers to the separability of the most difficult categories to separate. [43].

JMD was used in the project to assess the potential of satellite data for classification [42]. Apart from that, the measurement was also used for choosing the ideal features for classification [43, 45].

JMD has the advantage that the calculation can be made with any number of features. Additionally, the number of features necessary for a particular precision requirement can be determined. The method's weakness lies in the assumption that the probability density functions are normally distributed.

This procedure is suitable for choosing the best features for a parametric classification procedure. It is especially recommended when more than eight features are present, and the categories are characterised by a normal distribution.

3.4.8 Parallel-epiped classification

A parallel-epiped algorithm is a non-parametric procedure, where an upper and lower limit value is established in each band in order to delimit a category [57].

The determination of these limits can be done visually whereby frequency distributions are analysed. This process usually leads to better results, but it requires, depending on the separability of the category, a great deal of experience and an instinctive feeling. Alternatively the limits can be determined automatically (e.g. by means of mean values and standard deviations), which corresponds more to the requirements of an operational use.

This method was used for the classification of the degree of forest mixture in the Beckenried research area [43]. For TM and XS data, the limiting values were determined using the visual analysis of histograms. This resulted in an improvement of 14% compared to a minimum distance classification, and an improvement of 5% to 8% when compared to a maximum likelihood classification.

These examinations show that for certain tasks, significantly better classification results can be achieved with the help of the parallel-epiped method than with statistical classification methods. In addition, it allows features to be processed for which the frequency distribution of a category can not be approximated by a normal distribution. Given the increasing number of categories and features, the determination of upper and lower limits becomes very complex. As a result, visual analysis of frequency distributions for operational use is hardly feasible. This procedure is therefore recommended for simple differentiations, e.g. forest/non-forest classification.

3.4.9 Minimum distance classification

In the minimum distance classification, an image element is labelled with the category, to which it has the shortest distance to the centre of mass. As distance measurement, the Euclidean distance is generally used, in rare cases also the Mahalanobis distance. The centre of mass of a category can be defined by the mean or mode vector, or also by a centre, which is determined by an unsupervised cluster algorithm [57].

The minimum distance procedure was used for the classification of the degree of forest mixture with TM and XS data in the Beckenried research area [43]. The achieved accuracy was clearly below the accuracy of the parallel-epiped or maximum likelihood methods.

In the Yverdon research area, this procedure was applied for the classification of nine different cultivated areas [45]. Multitemporal TM and XS data from five different acquisition times were used. The procedure was preferred to the maximum likelihood algorithm since it usually reacts less sensitively with multimodal distributed training data and therefore leads to slightly better results.

The method is, above all, suitable for uncorrelated bands. In these cases, better results can sometimes be achieved than with the maximum likelihood method. However, in practice a strong correlation often exists between the bands, so that a maximum likelihood classification is preferred.

3.4.10 Maximum likelihood classification

With the help of a training dataset, the maximum likelihood algorithm calculates a multidimensional probability function for each category in the form of a normal distribution. Based on the density function, every pixel in the image is labelled with the category having the maximum likelihood. If it is known how often a category appears in the research area, the density function can be weighted with the so-called a priori probability [57].

Weighting by a priori knowledge is, however, not unproblematic: If the categories are weighted with their actual frequency in the research area – a prerequisite is that these are known – this leads to an overvaluation of frequently occurring (“big”) categories, while rarely occurring (“small”) categories will be undervalued. In some cases, such small categories may even completely disappear [70].

The maximum likelihood method was applied in the Beckenried research area for the differentiation of the degree of forest mixture with the help of TM and XS data [43]. The classification accuracy of both sensors was clearly below that of the parallelepiped method. In comparison to minimum distance classification, however, an improvement of approximately 5% was achieved.

This method was applied on TM data in Yverdon, within a hierarchical classification for the differentiation of the four main land use categories as well as for industrial and residential areas [43].

In the same research area, the maximum likelihood method was used for a land use classification. Müller [47] identified eight categories based on XS or TM data, while Dousse [22] differentiated nine categories using XS data. With the maximum likelihood method, Dousse achieved an improvement of the classification of 1.5%, compared to a neural network classification.

This method is simple and, with normally distributed features, it very often leads to optimal results. It is recommended for general land use classifications, where multispectral data of an acquisition are used.

3.4.11 Probability-based classification

The probability-based classification used within the framework of the project is based on the possibility theory introduced by Zadeh [73]. This theory, based on fuzzy logic, is useful to deal with imprecise and uncertain knowledge.

The membership grade can be described with linguistic predicates (e.g. “very low”, “high”, and “not”) [8]. Alternatively the membership grade can also be estimated analytically (e.g. via a maximum likelihood procedure) [71]. Thereby, information from different sources can be combined.

The probability-based procedure was used in the Beckenried research area in order to include the terrain elevation in the classification of the degree of forest mixture [43]. The membership grade regarding the terrain elevation was determined with help of linguistic predicates, while the membership grade regarding the spectral information was estimated with help of the maximum likelihood procedure. For the three categories deciduous, mixed and coniferous forest, an improvement of 5% to 12% was achieved with this method as compared to the maximum likelihood algorithm.

In the Yverdon research area, this process was applied within a hierarchical classification of TM data for the differentiation of the degree of forest mixture as well as for the differentiation of agricultural areas [43]. Besides the terrain elevation the exposition was also used for the definition of expert rules.

This method forms the basis for the evaluation of overlapping areas in XS and TM data of 17.10.95 [47]. In the Yverdon research area an improvement of 4% for TM data and an improvement of 7% for XS data was achieved, as compared to a maximum likelihood classification.

The advantage of a probability-based classification lies in the possibility of determining membership grades with help of expert rules as well as with analytical estimations. Gaussian and non-gaussian distributed data can thereby be linked without any problems. For operational use, the definition of expert rules could prove to be disadvantageous. This presupposes corresponding experience on the part of the interpreter. This method is especially suitable for complex differentiations, in which additional features, as for example terrain elevation, are needed or for multitemporal evaluations, in which numerous data sets are available for the same area [46].

3.4.12 Classification with neural networks

In the last years, neural networks have become a popular non-parametric approach to classification. They differ significantly from the conventional methods because the discrimination function is determined in an iterative fashion [14].

Within the framework of the project, the multilayer perceptron method was tested, which is the most commonly used neural network for the classification of remote sensing data [22]. This method is characterised by fast processing, is very well documented and has already been used successfully in many applications.

In the Yverdon research area, the method of neural networks was applied to classify nine land use categories based on XS data, terrain information as well as textural information [22]. In the same research area, the method was applied to differentiate nine agricultural areas with help of multitemporal TM and XS data. Compared to a minimum distance classification with the same satellite data, an improvement of classification of 6% was achieved [46].

The advantages of neural networks are the ability to learn, the capability of generalization, as well as tolerance of errors. The distribution of features does not play a role in this procedure. A disadvantage is the relatively long time the network needs to learn or train.

Classification with neural networks is therefore especially suitable for complex differentiation, where additional features such as neighbourhood, texture and terrain information are necessary, as well as for the differentiation of agricultural areas with help of multitemporal data.

3.5 Post-processing a classification

When post-processing a classification, a difference can be made between

- plausibility and
- generalization.

With plausibility, the classification result is checked using location characteristics (e.g. neighbourhood, height above sea level). This post-processing is usually done with the help of if-then-rules.

The aim of generalization is the processing of the classification results for cartographic representation. Usually the appearance of the classification result is smoothed by, for example, removing isolated pixels with the help of a filter. The resampling of a classification result with regard to the presentation in a certain scale, can likewise be counted as generalization.

In practice it is not easy to distinguish between the two post-classification methods. The removal of isolated deciduous pixels with a spatial resolution of 25 m is a priori a generalization. In practice such a small area is not defined as own stock, for which reason the removal of an isolated pixel also represents plausibility in this case.

Within the framework of the project, the classification results are post-processed only with the help of a modal filter. In the Beckenried research area, the probability-based classification of the degree of forest mixture was generalized and plausibilized with the help of a 5 × 5 modal filter [43]. For the three categories, an improvement in classification of 2% was achieved.

The same procedure was also used for the classification of the degree of forest mixture in the Yverdon research area. In addition, the result of the classification of agricultural areas was post-processed using a 3 × 3 modal filter [43]. A quantitative examination of the achieved improvements did not take place.

In the same research area a 3 × 3 modal filter was used in order to post-process the result of a multitemporal classification of nine different cultivated areas [45]. The classification accuracy could thus be improved by 2%.

4 Results

4.1 Overview

Within the framework of the project, classifications were carried out in the research area of Beckenried and that of Yverdon. Differences exist in relation to the satellite data used, the data pre-processing, as well as the classification methods applied. The aim of the classifications was the differentiation of the degree of forest mixture as well as of the land use.

To assess classification accuracies, the results were checked with the help of ground truth data. It is assumed that these reference data are correct to 100%. This assumption, however, is rarely correct and can lead to a false assessment of the classification result. The interpretation of the classification accuracy therefore requires accurate knowledge about the data collection methods (ground truth data and classification data). Likewise, the technique of accuracy assessment must also be clear. In the following the so-called overall accuracy will be indicated for the classification assessment. A description of this measurement can be found in chapter 3.4.2.

All classification results are referenced to the same geometric basis as the Swiss topographic maps. They are based on the Swiss geodesic datum CH-1903 (reference ellipsoid of Bessel (1841), basal point at the old planetarium in Berne) and the Swiss projection system (conform oblique cylinder projection).

Several examples of the classification results are presented in colour on the centre pages of this publication (p. 31–34). For each result the underlying satellite data, the processing steps carried out, as well as the results from the comparison with ground truth data, are cited.

4.2 Degree of forest mixture in the Beckenried research area

The corresponding Figure 7 is in the middle of this publication (see p. 31)

Satellite data:	Landsat TM scene 195/027 from 11.07.1991.
Post-system correction:	Removal of duplicated lines.
Geometric correction:	Empirical orthorectification. Resampling: nearest neighbour to 10 m.
Radiometric correction:	Semi-empirical radiometric correction (c-correction). Correction category: vegetation.
Classification:	Probability-based classification. Features: TM2, TM4, TM5, TM7, terrain elevation DHM25. Post-classification: modal filter 5 x 5.
Legend:	1: Deciduous forest 2: Mixed forest 3: Coniferous forest 0: Non-forest
Ground truth:	Forest stand map Brennwald/Schellenberg from IR aerial photographs 1987. Forest stand map Buochserwald from IR aerial photographs 1985. Overall accuracy: 57.0%.
Literature:	[43]

4.3 Land use in the research area Yverdon (monotemporal)

The corresponding Figure 8 is in the middle of this publication (see p. 31)

Satellite data:	Landsat TM scene 195/027 from 09.08.1990.
Post-system correction:	Removal of duplicated lines.
Geometric correction:	Empirical orthorectification. Resampling: nearest neighbour to 25 m.
Radiometric correction:	Physically-based radiometric correction. Data base: Radio sonde measurements and estimation of horizontal visibilities.
Classification:	Hierarchical classification. Maximum likelihood with the features TM3, TM4, TM5, TM7. Probability-based classification with the features TM2, TM3, TM4, TM7, terrain elevation DHM25. Maximum likelihood with the features TM1, TM3, TM4, TM5. k-means with the features TM3, TM4, TM5, TM7. Post-classification: modal filter 3x3 and 5x5.
Legend:	1: Deciduous forest 2: Mixed forest 3: Coniferous forest 4: Industrial areas 5: Buildings 6: Vineyards 7: Agricultural areas 1 8: Agricultural areas 2 9: Agricultural areas 3 10: Agricultural areas 4 11: Alpine agricultural areas 12: Lakes 0: Null category
Ground truth:	Swiss land use statistics 1992/97. Overall accuracy: 84.0%.
Literature:	[43]

4.4 Land use in the research area Yverdon (multitemporal)

The corresponding Figure 9 is in the middle of this publication (see p. 34)

Satellite data:	Landsat TM scene 195/027 from 08.04.95. Landsat TM Scene 195/027 from 03.05.95. Landsat TM scene 195/027 from 20.06.95. Landsat TM scene 195/027 from 22.07.95. Landsat TM scene 195/027 from 24.09.95. Spot HRV-XS scene 050/255 from 19.07.95.
Post-system correction:	Removal of duplicated lines (TM).
Geometric correction:	Parametric orthorectification. Resampling: bilinear to 25 m.
Radiometric correction:	Physically-based radiometric correction. Data base: Atmospheric models, aerosol models, image-based horizontal visibilities.
Classification:	Probability-based classification. Features: TM1, TM2, TM3, TM4, TM5, TM7.
Legend:	1: Deciduous forest 2: Coniferous forest 3: Settlement and urban areas 4: Construction sites, bare land 5: Transportation areas 6: Lakes 7: Rivers 8: Agricultural areas
Ground truth:	Swiss land use statistics 1992/97. Overall accuracy 88.7%.
Literature:	[46]

4.5 Agricultural cultivation in the research area Yverdon

The corresponding Figure 10 is in the middle of this publication (see p. 34)

Satellite data:	Landsat TM scene 195/027 from 08.04.95. Landsat TM Scene 195/027 from 03.05.95. Landsat TM scene 195/027 from 20.06.95. Landsat TM scene 195/027 from 22.07.95. Landsat TM scene 195/027 from 24.09.95. Spot HRV-XS scene 050/255 from 19.07.95.
Post-system corrections:	Removal of duplicated lines (TM). Removal of local noise (TM).
Geometric correction:	Parametric orthorectification. Resampling: bilinear to 25 m.
Radiometric correction:	Physically-based radiometric correction. Data base: Atmospheric models, aerosol models, image-based horizontal visibilities.
Classification:	Neural networks. Features: TC1 (08.04.95), TC2 (08.04.95), TC3 (08.04.95), TC1 (03.05.95), TC2, (03.05.95), TC3 (03.05.95), TC1 (20.06.95), TC2 (20.06.95), TC3 (20.06.95), XS1 (19.07.99), XS2 (19.07.99), XS3 (19.07.99), TC1 (22.07.95), TC2 (22.07.95), TC3 (22.07.95), TC1 (24.09.95), TC2 (24.09.95), TC3 (24.09.95), Terrain elevation DHM25, slope DHM25, aspect DHM25.
Legend:	1: Barley 2: Rye 3: Wheat 4: Peas 5: Potatoes 6: Maize 7: Rapeseed 8: Sugar beets 9: Meadow 0: Others
Ground truth:	Ground survey 1995. Overall accuracy: 76.4%.
Literature:	[46]

5 Conclusions and outlook

5.1 Conclusions

From 1990 to 1998 the Department of Geography of the University of Zurich (GIUZ) was contracted by the Swiss Federal Statistical Office (SFSO) to investigate a variety of methodical approaches to satellite data processing with the aim to evaluate the application potential of satellite remote sensing for official statistics, especially land cover, land use and environmental statistics.

These studies revealed that many of the methods developed abroad proved not or only to a limited extent suitable for processing satellite imagery of Switzerland. The topographical conditions and characteristics of land use in Switzerland called for new, specifically adapted methods for geometrical and radiometric corrections as well as for image classification.

The available ressources in the framework of the research cooperation would not have been sufficient alone to successfully conduct all the necessary tests and look into the relevant new developments. Fortunately, the project could benefit from synergies with other GIUZ research projects, mainly concentrating on the topics of forest classification and radiometric corrections. Making use of these combined efforts and liberally sharing experiences and results finally allowed significant progress in different areas of satellite data processing and the development of new and operational methods. The establishment of knowledge and experience in both these fields is judged as a success by both the client as well as the contractor of the studies.

The temporal and thematical phase structure of the research project has fostered flexible and efficient planning and management and finally led to valuable results. After evaluating in a first project phase to which extent satellite data could possibly match the requirements of official statistics production, four successive project phases of an average duration of one and a half years each were agreed upon. At the end of every phase, the research topics and targets of the next phase were intensively discussed and defined mutually by the client and the contractor. The project could therefore always re-orient itself according to the latest developments in statistics and in satellite remote sensing.

The decision to transfer much of the knowledge gained from the university research environment to the production environment at the SFSO is considered a significant milestone. Looking back, the start of this know-how transfer in the form of a new forest differentiation project, after about two thirds of the research cooperation was completed, seems to have been an optimal choice.

It is remarkable that there were very little personnel fluctuations during the entire project: the project management at the GIUZ as well as the accompanying project team of the SFSO remained stable over all these years. This continuity contributed significantly to the successful completion of the project in its entirety.

At the end of this research collaboration, both the client and the contractor can make use of methods for the processing of satellite data and the generation of land use statistics which are judged highly advanced in an international comparison.

5.2 Outlook

Motivated by the results of the research, the SFSO decided in 1996 to use digital satellite imagery to perform a forest differentiation for the entire area of Switzerland, complementing its established land use statistics (Arealstatistik) by additional information on forest mixture (deciduous, mixed and coniferous trees). This project is due to be completed by the end of 2000. Its results will hopefully contribute to further define the application potential of satellite remote sensing for statistical exploitation by the SFSO.

There is no doubt that satellite remote sensing will continue to advance technically as well as methodically. Since the end of the research collaboration between GIUZ and SFSO, another three revolutionary satellites have been brought into orbit:

- Landsat-7 with its enhanced thematic mapper (ETM+) sensor,
- IKONOS-2 whose sensor is capable of delivering four-channel multispectral data at 4m ground resolution and panchromatic information at 1m ground resolution,
- EOS AM-1 and EOS PM-1 whose sensor MODIS can be configured according to the task to be completed: it measures reflectance in three spectral bands at 250m, or in 18 bands at 1000m ground resolution.

In the next years additional spatially and spectrally high resolution sensors will be brought to orbit: OrbView-4 (end of 2000), Envisat-1 MERIS (2001), SPOT-5 (2002).

These new satellite data will definitely offer solutions for certain classification problems caused presently due to pixels of mixed spectral reflectance. At the same time, new problems will arise giving new scope for research and offering new challenges when developing operational applications. The amount of available data will multiply in future, while spatial texture and shape characteristics as well as the hyperspectral properties of objects will gain increasing importance.

Abbreviations and glossary

Banding	Banded pattern in row and column direction of a raster image due to varying calibration of a detector array during acquisition.
BRDF	*B*idirectional *R*eflectance and *D*istribution *F*unction; reflection characteristics of an object in the hemisphere.
CORINE	*C*o*OR*dinated *IN*formation on the *E*nvironment; programme of the European Community, started in 1985 and consists of different projects (among others CORINE Landcover).
DEM	*D*igital *E*levation *M*odel (also: digital terrain model, DTM); digital representation of the elevation information of an area, mostly in raster format.
ESA	*E*uropean *S*pace *A*gency.
ESRIN	*E*uropean *S*pace *R*esearch *In*stitute, Frascati, Italy; centre created by the ESA for the reception, processing and archiving of data from different sources (mainly satellite data).
ETM+	*E*nhanced *T*hematic *M*apper; sensor on the American platform Landsat-7.
Eurimage	Commercial provider of the ESA; Via E. D'Onofrio 212, I-00155 Roma, Italy; http://www.eurimage.it/.
Feature	Image information on objects acquired by sensors; among others grey tone, colour, multispectral signature, surface structure (texture), shape or temporal behaviour.
FOV	*F*ield *O*f *V*iew; total range of viewing of a sensor into the direction of the target, see also IFOV.
Frame	Reference of a scene across the flight direction.
GEOSTAT	Geographic information system and service centre of the Swiss Federal Statistical Office for spatial data (including services and coordination tasks).
GIS	*G*eographic *I*nformation *S*ystem; general name for a computer system for the collection, management, processing, analysis and representation of spatial data from different sources.
Grey value	Intensity value of a pixel (digital number).
Ground truth	Information gathered by in situ observations or measurements (on or close of the surface), describing the actual status of an object during data acquisition [20].
HRMSI	*H*igh *R*esolution *M*ultispectral *S*tereo *I*mager; sensor on the American platform Landsat-7, spatial resolution panchromatic: 5 m, multispectral: 10 m.
HRV	*H*igh *R*esolution *V*isible; opto-electronic array camera, sensor of the French platforms SPOT-1, -2 and -3.

IFOV	*I*nstantaneous *F*ield *O*f *V*iew; angular aperture within which a detector element is sensitive to electromagnetic radiation, see also FOV.
Integration time	Time, allocated by a sensor for the measurement. Depending on acquisition type this value can refer to a single pixel, a pixel array or a pixel matrix.
IR	*I*nfra*r*ed; wavelength interval from 0.7 to 12 (15) µm, see also NIR, TIR, VIS and SWIR.
Lambertian radiator	Object having a directionally independent reflection; this optical property may be regarded to be an ideally diffuse reflection.
Land use category	Type of a land use (in Switzerland) according to the category catalogue of the Swiss land use statistics.
Landsat	*Land Sat*ellite; American platform for the sensors RBV, MSS and TM.
LEDA	*L*andsat online *E*arthnet *D*ata *A*vailability; satellite image data base of the company Eurimage for Landsat, AVHRR, MOS and NIMBUS-7; open to the public via Telnet (epocat.esrin.esa.it).
LST	Local Solar Time; the local time where the sun is used as reference. Noon would be when the sun is at its highest point. It can be determined by a sundial.
MESSR	*M*ultispectral *E*lectronic *S*elf *S*canning *R*adiometer; opto-electronic array camera, sensor on the Japanese platform MOS.
MOS	(1) *M*odular *O*pto-electronic *S*canner, also *M*ultispectral *O*ptical *S*ensor; opto-electronic array camera, sensor on the Indian platform IRS-P3 and (2) Marine Observation Satellite; Japanese platform for the sensor MESSR.
MSS	*M*ulti*s*pectral *S*canner; opto-mechanical scanner, sensor on the American platform Landsat-1, -2, -3, -4 and -5.
Multitemporal	Approach, which considers acquisitions or sources with different recording time.
NIR	*N*ear *I*nfra*r*ed; wavelength interval from 0.7 to about 1.3 µm, see also VIS, SWIR and TIR.
Pan	*Pan*chromatic mode of the sensors HRV.
PAN	Panchromatic Camera; opto-electronic array camera, sensor on the Indian platform IRS-1C and -1D.
Pixel	Picture cell, also picture element; area unit of a digital image, which is identified by a specific position and a grey value within the image matrix; in case of colour or multispectral images, it is identified by several grey values [20].

RBV — *R*eturn *B*eam *V*idicon; opto-electronic image camera, sensor on the American platforms Landsat-1, -2 and -3.

Resampling — Process, which computes a new grey value matrix from an existing one during geometric transformation of an image; it is linked to an interpolation of the input image values [20].

RGB — *R*ed-*G*reen-*B*lue.

RMSE — *R*oot *M*ean *S*quare *E*rror; measurement for the approximation of two data records.

SAR — *S*ynthetic *A*perture *R*adar; imaging radar system with across flight direction view and with synthetically increased antenna size (aperture).

SFSO — Swiss Federal Statistical Office, Neuchâtel .

SPOT — "*S*atellite *p*our l'*o*bservation de la *t*erre", also "*S*ystème *p*robatoire d' *o*bservation de la *t*erre"; French platform for the sensor HRV.

Stand map — Map of forestry institutions; it contains information of the actual wooded areas and composition.

Striping — Striped pattern in row and column direction of a raster image due to varying calibration of a detector during acquisition.

Sweep — Sweep of a mirror over the earth surface on an opto-mechanical scanner; e.g. on TM, 16 parallel lines are recorded.

SWIR — *S*hort *W*ave *I*nfra*r*ed; wavelength interval between 1.3 to 3.5 µm, see also VIS, NIR and TIR.

TIR — *T*hermal *I*nfra*r*ed; long-waved, emitted infrared, wavelength interval between 6 to 12 (15) µm, see also VIS, NIR and SWIR.

TM — *T*hematic *M*apper; opto-mechanical scanner, sensor on the American platforms Landsat-4 and -5.

Track — Nadir line of a satellite overflight; also path.

VIS — *Vis*ible electromagnetic radiance, wavelength interval from about 0.4 to 0.7 µm, see also NIR, SWIR and TIR.

WRS — *W*orld *R*eference *S*ystem; grid defined by tracks and frames for the precise localisation of a satellite scene.

XS — Multispectral mode of the sensor HRV.

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In 1990, the Swiss Federal Statistical Office requested the support of the Department of Geography of the University of Zurich to assess the feasibility of satellite remote sensing for land use statistics. This first research contract was followed by another four until 1997. This publication provides an overview of the methods used and developed and the results achieved during the five project phases.

A general introduction is followed by an outline of the development and application potential of remote sensing, the description of the satellite systems and data used for the research areas of Beckenried and Yverdon during the project, and the presentation of the base data set from the Swiss land use statistics. A discussion on the optimal season of satellite image exposure and on the availability of cloud-free satellite scenes of Switzerland winds up the second chapter.

The main part of the publication identifies the methods which were tested and developed for preprocessing and classification of satellite data within the framework of the project. Next to a synoptical description of the major established methodical approaches, the procedures involved are documented extensively, and the results achieved with their help presented and evaluated. The results chapter illustrates some examples of land use classifications achieved with different methods, in different areas, and targeted at different categories.

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