Toward Automatic Quality Control and Change Detection for DTM

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by

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To my father
Abstract

The quality of geospatial data receives much more attention than ever. The existing GIS data come to be used as prior information for updating geospatial database with imagery. The existing DTMs may be good enough for some applications, but as the demand for higher resolution and higher accuracy data rises, they cannot meet the requirements due to some errors introduced from the source data and production methods. On the other hand, some changes may happen in the terrain relief because of the natural erosion, landslide, earthquake, and the human activity. These changes should be reflected in the DTMs. This research plans to develop tools and experimentally tests several concepts aiming at automatically updating and upgrading a “medium scale” DTM with IKONOS images or aerial photographs.

Spectral analysis is adopted in this research to estimate the accuracy of the DTMs. To detect the terrain change, a method is developed in this research. It assumes that the big difference between two DTMs is the result of terrain change or errors such as insufficiently filtering protruding objects, in particular trees and buildings. This method finds the pattern of cutting and filling along the road buffer and steep slope from the difference of two DTMs, and analyzes the possible reasons of big difference in the critical regions of the forest, urban, road, and steep slope. Based on these concepts, a global workflow for DTM updating with high resolution satellite images is proposed.

The spectral analysis method for accuracy estimation and appropriate program are testified on a sinusoidal wave. A DTM generated from IKONOS stereo images are compared with an existing DTM. From the difference of these two DTMs, the error related to coordinate reference is detected. With the discriminant, the reason of poor filtering for big difference between the unfiltered and filtered DSM is determined.

A knowledge-based filtering approach is developed and partly implemented for the case of high resolution DSM of a flat area. This approach takes advantage the elevation difference between the neighbor pixels in the DSM to form the edges of the objects, and then track the edge pixels to reconstruct the border of the cluster. The substitution or interpolation method is applied to rectify the elevation values according to the cluster type. To delineate the outer border of a cluster, an efficient border tracking algorithm is designed too. With this algorithm, some complex border tracking can be accomplished. The acquired filtering result is good with the building objects and forest blocks, but poor in the elongate road covered with vegetation.

Keywords

digital elevation model, digital terrain model, quality control, change detection, border tracking, filtering
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1. Introduction

1.1 Background

Geographic information systems (GIS) are broadly used in today’s life. It is estimated that about eighty percent of the decisions from public authorities and private industry are made using geospatial data (Gerke, Butenuth et al. 2004). The quality of geospatial data receives much more attention than ever. Supplying accurate and current geospatial data becomes a basic task of the mapping agency. When updating the geospatial data, large amount of time and human resources are currently spent on checking whether the information is still up to date (Vosselman, Gorte et al. 2004), and it holds for Digital Terrain Model (DTM). DTM is a description of the geometry of the ground surface, based on higher number of points with planar and vertical coordinates. Another term, DEM (Digital Elevation Model), often shares the same meaning as DTM, that is, if the elevation is understood to refer to the ground surface. In some circumstances, DTM may mean those DEMs that incorporate topographic features, which are irregularly spaced, so as to characterize the shape of the terrain. To avoid confusion, DTM is used in this thesis.

Nowadays, DTM has become a standard geospatial product. It can be used in the fields of civil engineering, mining, surveying and mapping, geosciences, and land management. The most often used photogrammetric product, orthoimage, is generated by means of a single image and a DTM. To save capacity, the very high-resolution space sensors are mainly operating in a single image mode; stereo pairs are not taken very often. Thus DTM is necessary for correct geo-referencing these images (Jacobsen 2003).

The classical means of DTM generation are digital photogrammetry, analytical photogrammetry, ground survey, and interpolation from digitized contours. The first three methods are more accurate but time consuming. For the DTM production with optical image, two or more images showing the same area from different directions are needed. To correctly determine the ground point, the projection center and the view direction are needed. The last method is suitable for mass-production with the advantages of short time and low cost.

The generation of DTM is quit possible with the high resolution satellite images. It has shown that high resolution satellite images, such as SPOT, IKONOS, QuickBird, as well as Interferometric Synthetic Aperture Radar (InSAR) and Light Detection and Ranging (LIDAR), are suitable to produce DTM (Gomes Pereira and Janssen 1999; Jacobsen 2003; Holland and Marshall 2004; Jacobsen 2004). The process of producing DTM using satellite images includes three main steps, image orientation, automatic image matching, and surface modelling. The image orientation was done with information of the view direction together with the general orbit information and control points. After that the
image matching is carried out automatically to find the match points in the image pairs. Although the automatic image matching can acquire the same accuracy for the matched ground points as human operator, the selection of bare ground points is challenging. The selected points are not always on the ground; they may be the points on top of buildings or vegetation, or even mismatching. In contrast, a human operator can set down the floating mark from the building top to the ground. The automatic image matching cannot generate DTM, only Digital Surface Model (DSM) with the points located on top of visual objects. The same problem exists in the methods of LIDAR and InSAR. The DSM filtering is necessary to produce DTM and the final product has to be edited by human operator. It degrades the efficiency of automatic processing. It is stated that the amount of data produced in fifteen minutes of automatic matching a stereo pair may require up to five hours to check and edit using manual and computer-assisted techniques (Norvelle 1996).

In open area the standard photogrammetry method for DTM production is more economic, while in the forest area the LIDAR method has advantages. In the mountainous areas and terrain with steep slopes, though, both methods are not very good. It is believed that in the higher precision usage environment LIDAR will become dominating. Automatic image matching will be used in the medium accuracy range. The upcoming digital aerial cameras may change the use of different sensor systems again because of the capability to produce highly redundant data and thus reliable products. In the lower accuracy and wide area application, InSAR is expected to be used more and more. Different methods may complement each other depending upon the local conditions. In any case, the derived digital surface model should be rectified to DTM automatically (Jacobsen 2002).

1.2 Problem formulation

Most of existing DTMs were generated from contour lines. In Europe and in North America it is a mixed situation and existing DTM have different sources. The existing DTMs may be good enough for some applications, but as the demand for higher resolution and higher accuracy data rises, they cannot meet the requirements due to some errors introduced from the source data and production methods. On the other hand, even though the terrain is relative stable, comparing with man-made features, some changes may still happen in the terrain relief because of the natural erosions, landslides, earthquakes, and the human activities. These changes should be reflected in the DTMs.

In China, the DTMs of 1:250000 scale have been established, which include 816 map units of 1.5 degree in longitude and 1 degree in latitude. The data sources are of the same scale topographic maps. DTMs of 1:50000 are components of 1:50000 scale topographic databases. They have also been established and cover seventy to eighty percent of the country with more than 19000 map units of 15 minutes in longitude and 10 minutes in latitude. The 1:50000 scale DTMs were mainly produced with the method of interpolation from digitized contours. Some were produced from aerial photographs. In the mean time, topographic databases of 1:10000 scale are under construction. DTMs of 1:10000 scale in the flood area are available now. The updating of 1:50000 topographic databases have been put on the agenda of The State Bureau of Surveying and Mapping (SBSM) of China. The same updating tasks are also planned for the 1:10000 scale DTMs.
It is not economic to update the whole DTMs of 1:50000 scale and 1:10000 scale in China with LIDAR method. Meanwhile, the high accuracy requirement cannot be met with the InSAR data. The economic and feasible method for updating medium to high resolution DTMs in China should be automatic image matching with aerial photos or satellite images.

Although it is possible to generate a new DTM using high resolution satellite images, it would not be very wise to simply throw away existing data and blankly produce a new DTM. The reason is the automatic image matching can only generate DSM, and DSM filtering is not very easily carried out. The final filtering product still need human checking and editing, which is time consuming at the present state of the art. By all means, the existing DTM is a useful information source. It is likely to be more efficient to automatically evaluate the existing DTM and detect the areas of low accuracy or of change, and then upgrade or update only these areas using the new data source.

The motivation of this research is to find a method to update or upgrade medium to high resolution DTMs, combining the efficiency of automatic image matching technology, the relative cheap source of high resolution satellite images, and the useful information in the existing DTM.

1.3 Previous work

One research direction related to DTM is the selection of sampling grid size and interpolation method, as well as their effects on the DTM quality (Ackermann 1996; Tempfli 1999). DTM quality and its effects on the derived information, such as slop and aspect, is another research direction and examples can be found in (Skidmore 1989; Holmes, Chadwick et al. 2000; Hengl, Gruber et al. 2004). With the emerging of new technologies or new satellite images, such as InSAR, LIDAR, and Spot 5 HRS images, some researches are carried out on the accuracy estimation of DTMs generated from these sources (Gens 1999; Gomes Pereira and Janssen 1999; Rudowski 2004). Research on DSM filtering, especially for DSM generated with LIDAR, is another research topic related to DTM (Jacobsen and Passini 2001; Marmol and Jachimski 2004; Sithole and Vosselman 2004).

Accuracy assessment and error elimination for DTM is a constant research topic. Classical method of estimating the accuracy of DTM is using checkpoints, as stated in USGS standards for DTM. Some researches are focused on the accuracy estimation without using checkpoints and reference DTM (Gens 1999; Tempfli 1999). Recognition and reduction of systematic error is presented in (Brown and Bara 1994). Methods for detecting and correcting the gross errors and some random errors in DTM are presented in (López 2000).

Photogrammetry and remote sensing were used as a main method of data acquisition and updating for GIS database. Nowadays, the bi-directional links have been established since the existing GIS data come to be used as prior information for updating with imagery (Heipke, Pakzad et al. 2000). Similar research can be found in (Willrich 2002), which presents an approach for automatic quality control and updating of the existing topographic data set using imagery. With the additional knowledge derived from the existing scene description, roads are extracted automatically from the imagery. The extracted roads are then compared to the roads in the dataset to derive a quality description. Those
roads that are not accepted at the first evaluation will be processed with a detailed analysis of local situation and then be classified to rejected or undecided. An operator will check the undecided roads, to correct or complete the results and assure the road change.

Although many researches have been carried out on DTM, papers on DTM updating with high resolution satellite images can not be found. Apparently, in order to upgrade and/or update the existing DTM, the error prone area and change prone area should be delineated, which is the intention of this research.

Some commercial software, such as Leica Photogrammetry Suit (LPS), can be used to generate DTM from satellite images. ArcGIS can be used to analyze the existing DTM and newly generated DTM. Due to its powerful function on computing and data analysis, Matlab is suitable for carrying out some analyses not included in the above mentioned softwares.

1.4 Objectives

The objectives of this research can be described as follows:

- Identify DTM accuracy measures that are useful in explaining the difference between two DTMs of the same area.

- Analyze the necessity and possibility of filtering a DSM obtained by automatic image matching.

- Develop a concept for a procedure of automatic quality control for the purpose of delineating areas where an existing DTM should be updated or upgraded.

- Experimentally verified selected aspects of the developed concepts using automatic image matching as a source for the new DTM.

1.5 Research questions

To achieve the objectives set above, the following research questions are identified and dealt with in this research:

- What are the appropriate DTM accuracy measures, which can be estimated from the DTM data themselves without having to rely on extensive external reference data, and are suitable for detecting terrain changes?

- Which information should be available about the existing DTM?

- What are the characteristics of the satellite images having an impact on DTM accuracy?
• Which information is needed for delineating areas of possible low quality in order to upgrade the DTM, and for delineating areas of possible change in terrain relief to update? In which data source can the hints be found, old DTM, new DSM, the satellite images, or the difference between old DTM and new DSM?

• Are DTM accuracy measures derived from the DTM data sufficient for delineating terrain relief change and low quality in the DTM? Or is the additional information needed? Which additional information is needed?

### 1.6 Approach

To carry out these tasks, the following methods are applied in this research:

• Involve an in-depth study on automatic image matching, DTM quality issues, and DSM filtering. It will focus on the role of high resolution satellite images in the quality control and change detection for those DTMs generated from digitized contours. A workflow for DTM updating with high resolution satellite images will be proposed and some methods will be tested with an actual case.

• Analyze various geostatistical concepts for relevance and applicability in order to identify suitable accuracy measures for change detection. Analyze available software for offered quality tools. Develop new tools if necessary and test them. Develop a concept for identifying error prone area and change prone area.

• Investigate by experiments whether the candidate accuracy measures and estimation procedures can explain the differences between an existing DTM and a new DSM/DTM. If possible, we will use data from China and generate a DTM from high resolution satellite images automatically, analyze the accuracy of the newly generated DTM and then compare it with the existing DTM.

• Identify additional information needs for delineating the error prone area and change prone area, and the source of this additional information.

• Explore several filtering concepts and test one of them. As the product generated with automatic image matching is only DSM, the DSM product should be reduced to DTM to get the same elevation reference surface with the DTM, in order to find the error prone areas and change prone areas.

• Investigate segmentation methods to detect areas where errors most likely happen. Depending on the primary data source, these areas may include the areas of steep slope in DTM, roads, build up areas, and forest areas in satellite image.
1.7 Thesis outline

The thesis is organized as follows. The second chapter is the literature review, introducing the related research questions and current research status, as well as the characteristics of the IKONOS images. Chapter three presents the concept design for detecting error prone area and change prone area, including overall accuracy estimation without using checkpoints and reference data, critical regions delineation, the accuracy measure identification, gross error detection, analyses of big difference between the old and new DTMs, and suggested workflow for DTM updating with high resolution satellite images. Chapter four describes the test data, test results of some selected concepts, and analyses. As the effects of buildings and vegetation on the automatically extracted DTM are quite apparent, especially for the large scale case, the concepts and test results of a knowledge-based filtering are presented in Chapter five. Chapter six also gives an account of applying the error analysis concept on the filtered and unfiltered DSM from large scale aerial photographs. The last chapter is for the conclusions and recommendations.
2. Related literature

2.1 Automatic generation of DTM

It is summarized in (Schenk 1996) that three tasks are needed to fulfil in the automatic DTM generation from stereo images. They are image matching, surface fitting, and quality control. Image matching, or finding conjugate points automatically, is a fundamental task. Three best known matching methods are area-based matching, feature-based matching, and symbolic matching. Area-based matching is associated with matching gray levels by correlation or least-squares techniques, which are simply called correlation or least-square matching (LSM) respectively. In feature-based matching (FBM) conjugate properties (features) are derived from the images. Such properties include feature points, edges, and regions. Edges are the most often used features; edge operator should be direction independent, and be applied after the image smoothing to avoid the impact of noise. Symbolic matching methods compare symbolic descriptions of images and measure the similarity by a cost function. After image matching, surface fitting is needed to interpolate or approximate the terrain surface with the acquired point data. It is necessary because the points obtained by image matching are not evenly distributed and do not completely represent the surface, and some holes may exist due to unsuccessful matching. The final task is to check and edit the matching and fitting results by a human operator for accuracy and completeness reasons. It is a crucial and time-consuming task, generally comprising two steps, displaying DTM and editing the data if necessary.

It is also stated that the least square matching has the best accuracy, but it requires initial approximations to within a few pixels and locally flat terrain for optimum performance. In contrast, the feature based matching does not have these strict requirements; it can run fast and produce high data redundancy (Ackermann 1996). However, feature based techniques have difficulty in monotonous regions with few features (Gooch and Chandler 2001).

The vertical accuracy of automatically generated DTM of a rough area in different land use types were tested and the results were presented in (Bacher 1998). In this research, aerial photographs at the scale of 1:13000 were used to generate DTM with non-adaptive method (semi-automatic) and adaptive method (automatic), in combination with different strategies. The control data include 102 GPS points and 2700 photogrammetrically measured regular grid points with the attributes of land use, vegetation height, terrain roughness, and texture. The generated DTMs were compared to each other and compared with the control data. The results show that automatic methods yield best results in flat, open, and well-textured terrain, with the elevation accuracy better than one meter. The accuracies become bad in the areas of little texture and steep slope. At the edges of forest regions, along tree lanes, or in built-up area, the result cannot be used as DTM without filtering.
As already described, the automatic image matching can only generate a DSM. According to different applications, different surface model types may be selected. For example, DTM representing the ground surface without vegetation and buildings are best for hydrological studies; top surface model which is edited to building and treetops is best for line of sight analysis and aircraft navigation (Dial, Bowen et al. 2003). Meanwhile, DTMs with reference to the bare ground are generally needed. In digital cartography, contours shown on topographic maps require a DTM as input.

The automatic filtering of a DSM to a DTM is based on the relation of the neighboured elevation values; some methods are splines approximation, shift invariant filters, linear prediction, and morphological filters. It is reported that a linear prediction is applied to a photogrammetrically acquired DTM of very rough terrain with very dense bushes and buildings, 37.71 percent points of the total is eliminated with the type I errors (points belonging to the bare terrain but removed) of 0.78 percent and type II errors (points not belonging to the terrain but kept) of 1.88 percent (Passini, Betzner et al. 2002). Before the applying of linear prediction with covariance function, a low degree polynomial or a moving plane is accomplished to eliminate the trend from the given observations or signals. It is suggested to incorporate breaklines information in the filtering system to enhance the efficiency and reliability of the filtered data by minimizing the type I and type II errors.

Breaklines are linear features that describe a change in smoothness or continuity of the surface. Such abrupt surface changes are streams, shorelines, dams, and ridges. With the description of breaklines in DTM, the distinctive terrain features can be defined more clearly, contour lines generate from DTM can closely approximate the real shape of the terrain (Maune 1996). As the automatic image matching produces enormous points, approximately 500,000 or more points per stereo pairs, it is possible for automatic recognition of gross error and obstacles and eventually the automatic identification of breaklines (Ackermann 1996).

### 2.2 DTM quality control

Quality is often defined as “fitness for use”. Generally speaking we may say data quality includes six aspects, lineage, accuracy, completeness, logical consistency, semantic accuracy, and currency. Some recognized uncertainty includes error, vagueness, ambiguity, and discord. The similarity relations among uncertainty and data quality are listed in Table 2.1 (Fisher 2003).

Uncertainty exists in all types of geographic data. The theoretical frameworks employed in this area include traditional error analysis and geostatistics (Goodchild 2003). As to multi-spectral imagery, uncertainty could be introduced by spectral confusion between distinct land cover types, spatial mis-registration, topographic and atmospheric effects, and biases specific to the sensor (Bastin, Fisher et al. 2002).
Table 2.1  Similarity relations among uncertainty and data quality (Fisher 2003)

<table>
<thead>
<tr>
<th>Uncertainty</th>
<th>Data quality</th>
<th>Positional</th>
<th>Attribute</th>
</tr>
</thead>
<tbody>
<tr>
<td>Error</td>
<td>Accuracy</td>
<td>Completeness</td>
<td>Vagueness, Discord, and Ambiguity?</td>
</tr>
<tr>
<td>Vagueness, Discord, and Ambiguity?</td>
<td>Semantic accuracy</td>
<td></td>
<td>Error, Discord, Vagueness and Ambiguity?</td>
</tr>
<tr>
<td>Discord</td>
<td>Currency</td>
<td></td>
<td>Logical consistency</td>
</tr>
<tr>
<td>?</td>
<td>Lineage</td>
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</tr>
</tbody>
</table>

There are two meanings of quality control, a broad one and a narrow one. The broad quality control means a set of procedures that ensure quality output. It can be carried in two ways: pro-active way, that is implementing techniques and procedures that attempt to reduce errors and eliminate mistakes, and re-active way with reviewing all completed work to identify and correct errors before any product is released (Hoilett 1997). The narrow meaning of DTM quality control specifies the check and edit of DTM. It is the final task of DTM generation to ensure the accuracy of a DTM. In this research, the term of quality control adopts the narrow meaning.

It is believed that the most relevant quality aspects for a DTM are accuracy and currency. The accuracy of a DTM includes horizontal accuracy and vertical accuracy. Because the horizontal positions are mathematically fixed, the only measurable errors in a DTM are vertical errors (Tempfli 1999).

Root mean square error (RMSE) is dominating specification in the DTM accuracy report; it is defined on a probability level of 68 percent. Circular error at the 90 percent probability level, CE90, is also used in USA, it has a fixed relation of 2.1 to the standard deviation of the coordinates (Jacobsen 2003). Similarly, linear error at the 90 percent probability level (LE90) is often used as a measure for vertical accuracy.

The accuracy of an elevation value determined by the intersection of two imaging rays is related to the x-parallax error, which depends on pixel size, height to base ratio, and the contrast among the pixels. The height to base ratio is identical to inverse sum of the tangent of the nadir angles in the base direction. The x-parallax error is usually below a pixel. The elevation values in the DEM are then interpolated from the measured values. In the SPOT case, accuracy for the interpolated elevation values can reach 5 to 10m in open and more flat area (Jacobsen 2003); while in the case of SPOT 5 HRS images, the vertical accuracy can reach 4.1m in open area, 14.1m in forest area, and 5.7m in total, using DTM generated from laser scanning as reference data (Jacobsen 2004). These accuracy figures included all error influences, also the error propagated from the orientation procedure.

It is also argued in the literature that only the RMSE is not appropriate to report the error of the DTM, “a user cannot possibly know whether a RMSE of 2 m (for example) does or does not make a DTM fit for any particular use” (Fisher 1998). It is pointed out that there are a number of problems with the
RMSE measure. The first one is the assumption that the error is the same everywhere in the area of the DTM; the RMSE is stationary over any single study area. Secondly, it is an assumption of no bias in the errors. We agree that these assumptions are not always correct. However, we think whether RMSE can be used directly is depending on the application. Some applications, like orthophoto production, can directly use the RMSE measure of a DTM. Moreover, good production procedures will detect and correct systematic errors, at least to the amount necessary to meet the specifications.

DTM quality check can be done with different methods, such as point examination, visual checking, random sampling, joint map checking, section method, auto examination, and image examining (Zhu, Wei et al. 2003). An automatic examination method, analytical accuracy estimation, is proposed in (Tempfli 1999). In this paper, spectral analysis is used to estimate the internal accuracy of DTM. With certain assumption, a simple estimator of the variance of the DTM error can be deduced. In the mean time, a flow diagram of accuracy assessment of an existing DTM is given. The spectrum analysis method can be used in this research to provide a global internal quality estimate.

Geostatistics is another promising analytical approach for DTM accuracy assessment. First geostatistical approaches to DTM accuracy assessment were reported by (Kubik and Botman 1976). “Modern geostatistics aim precisely at constructing such local probability distributions for the unknown conditioned to nearby data” (Kyriakidis, Shortridge et al. 1999). In this paper, a geostatistical approach for data integration and accuracy assessment in DTMs is presented. Using stochastic conditional simulation, sparse measurements at high accuracy (called hard data) are combined with abundant DTM-reported elevation at low accuracy (called soft data) to generate the unknown higher accuracy elevation surface. A set of auto and cross-covariance models are produced to quantify the relation between hard data and soft data. Local uncertainty models are generated from the hard and soft data set via cokriging and then utilized to simulate the reference surface. The resulting simulated realizations of the reference surface reproduce aspects of both hard and soft data, and are utilized for constructing spatial measures of DTM accuracy. These accuracies can be expressed in the form of probability maps for the DTM-reported elevation to over or underestimate the unknown reference elevation, or maps of the corresponding local mismatch magnitude estimates. This method can be used to integrate two data sets to create useful realizations of high-density accurate data, and to evaluate the accuracy of the soft data with the hard data (Kyriakidis, Shortridge et al. 1999).

DTM contains gross errors, systematic errors, and random errors. Gross errors, also called blunders or outliers, may be introduced by gross misinterpretations or careless observations, undetected mismatches in image correlation, recording failures. Systematic errors are related to producing system or procedures in a predictable pattern and magnitude. Random errors are caused by accidental reasons; their magnitude can be predicted (Tempfli 1999).

Good quality control procedures aim at detecting and removing blunders and also systematic errors if larger than tolerable by specifications. Brown and Bara (1994) use semivariograms and fractal dimensions to analytically recognize the presence and structure of systematic errors in DEMs and suggest filtering as a means to reduce the error. Some methods for detecting and correcting the gross errors as well as some random errors in DTM are compared in (López 2000). One of the methods, proposed by Felicísimo in 1994, analyzes the difference between the elevation value and interpolated
value obtained from its immediate neighbours, and then a Student’s t test is applied to verify whether the elevation value is a candidate of gross error. This method assumes that outliers are only locally correlated. Another method, proposed by López in 1997, subdivides the DTM into elongated strip, and then analyzes the clouds of points with Principal Component Analysis (PCA) to find error prone points. A modified method is proposed to adapt the high spatial auto correlation situation, by the means of sub sampling the DTM at k-th row instead of forming strips. All three methods are used in an iterative fashion, until 15 percent of the elevation values have been corrected or confirmed.

Novelle (1996) describes a method to perform DTM quality control, called Iterative Orthophoto Refinements (IOR). The basic idea is to generate two orthophotos of the original stereo aerial photographs using DTM under investigation. If the DTM is correct, and the exterior orientation is accurate enough, the produced orthophotos should be identical. Any geometric mismatches in the orthophotos incur from wrong DTM. The mismatches can be measured with automatic image matching method, and then converted to elevation errors and used to refine the original DTM; new orthophotos can be produced again. These processes will repeat until there is no measurable difference between the orthophotos. It is shown by the test results that IOR method can improve the speed 10 times than manually edit, and no significant mismatches found in the new orthophotos after three iterations except in area of dense vegetation growth (Novelle 1996). Skarlatos and Georgopoulos (2004) develop this idea with direct correction in a specific position of the existing DTM, thus no need for iteration. It is proved that this method can calculate corrections in DTMs and improve their accuracy (RMSE) by 37 percent (real data case), and their precision by 40 percent approximately. We think that the defects of this method in dense forest area also hold for densely build up area. Since a good DSM may get in these areas and so does for an orthophoto referenced to this DSM, thus no or little error will show up when this method is applied. On the other hand, the elevations of the forest areas and build up areas are likely to be erroneous. So this method is not promising in this research.

In (Gooch and Chandler 2001), a software model named with failure warning model (FWM) is developed to assist the check and edit of automated DTM with figuring out the error prone areas. In most cases, digital photogrammetric system (DPS) software has a set of strategy parameters that can be adjusted by the operator to control the DEM generation process. Through many tests of different combinations of strategy parameters in different areas, it is found that strategy parameters only affect points with the highest residuals. Thus, FWM is developed to identify automatically such areas. By subtracting two DTMs of the same area generated using different strategy parameter settings, areas with unreliable elevation estimates are highlighted. Each point is given one of the three classifications in the output. The point where the software has interpolated the elevation in areas where slope angle is varying rapidly is classified as 0 (black area), the point with the value different from 0 meters in the different DTM is classified as 256 (white area), others do not change. This information is overlaid on an orthophoto of the area to get a hardcopy, which can inform the operator where to focus when check and edit. The FWM is tested with a large number of areas by comparing the RMSE of three class zones and the RMSE of the whole area. It is found that the white area zone has significantly higher RMSE than the overall RMSE, which is deemed that the FWM has highlighted the correct points with the largest residuals (Gooch and Chandler 2001). Since this method only supplies guide for the operator in manual editing, it is of little use in this research.
2.3 Change detection

Currency is one of the quality aspects and is clearly important in the use of information. Today a main duty of mapping agencies is to update geospatial data; such data cannot be updated unless it is known where topographic change has taken place. The currency checking is the most time-consuming work. Although the terrain relief is relatively stable, some changes may happen because of the natural erosion, landslides, and earthquake, as well as the human activities, such as civil engineering. DTM updating can be carried out by a complete reconstruction of the area for each revision cycle, but much time is likely to be saved by detecting changes from the previous version of the map database and concentrating on those areas of change.

There are many different ways to identify this change. One of the important ways is through local observation by surveyors in the field. Sharing information from other departments, such as land resource and urban planning, is another possibility. Because the high resolution satellite images have the attribute of high efficiency, high accuracy, and low expense, it could play an important role in the topographic change detection.

Most change detection research is focusing on terrain features instead of terrain relief. There are a lot of papers on the topic of the usage of satellite images in change detection and map updating. It is concluded that the well-known change detection techniques are image differencing, image ratioing, image regression, PCA, wavelet decomposition, and change vector analysis. The accuracy of change detection with satellite images is proportional to the image resolution, that is, the higher the resolution of the images used, the higher the accuracy of the change detection (Lampropoulos, Liu et al. 2004). More than 90 percent of the features are visually detected and identified successfully using SPOT 5 HRG in revision of 1:25000 topographic maps (Sadeghi Naeeni Fard, Abootelebi et al. 2004). Similarly, QuickBird image is found to be able to update mid-scale maps (1:6000 to 1:10000 scale) except for narrow linear features, such as electricity transmission lines, walls, fences and hedges (Holland and Marshall 2004).

The application of DTM in landslide quantitative analysis is presented in (van Westen and Lulie Getahun 2003). The Tessina landslide, located in Northeastern Italy, has happened several times since 1960. In 1992, two villages located in the downstream part of the Tessina landslide were threatened to temporary evacuation. Aerial photographys of this area are available for the year 1954, 1961, 1969, 1980, and 1991. A series of DTMs are generated from the available topographic maps for the year 1948, 1964, 1980, 1992, and 1993. Using these DTMs, photo pairs are orthorectified and interpreted to generate detailed landslide activity maps. The areas and volumes in the depletion and accumulation zones are analyzed quantitatively for each reactivation phase with these activity maps and DTMs. Based on these analyses, some valuable conclusions on the landslide are reached.

The research on landslide models could possibly contribute to delineate landslide prone areas, thus area to check for change. If we can automatically detect new roads or railroads, we may be able to detect relief changes too.
From the above literature, it can be found that generating a new DSM from high resolution satellite images is not difficult. At the same time, it is also not difficult to compute the difference between and existing DTM with the new DSM or DTM. But there is no integrated concept reported in literature on how to explain the difference: is it within the expected accuracy of the two surface representations, is there actual change of terrain relief, is there reason to change the old data because the new one is better, or is the new data worse?

2.4 Image segmentation

Segmentation is the subdivision of an image into homogenous regions or categories, which correspond to different objects or parts of objects. In (Jähne 2002), several segmentation methods are discussed. These methods are pixel-based methods, region-based methods, edge-based methods, and model-based methods. It is pointed out that the former three methods are based only on local information. Pixel-based methods only use the gray values of the individual pixels, thus have serious problems when the background is not uniform or the objects are not in the same gray level. Though inhomogeneous illumination can be corrected by dividing the image by the background image, a bias of the size of segmented objects cannot be avoided when objects varies in gray values. The problem of size bias can be avoided in edge-based methods. It is based on the fact that an edge can be detected with an extreme of the first-order derivative or a zero crossing in the second-order derivative of the gray value. Region-based methods analyze homogeneous regions with the techniques of split and merge or region growing. An edge-based segmentation approach can be used to avoid a bias in the size of the segmented object without using a complex threshold scheme. The edge-based segmentation cannot be performed on all the pixels. The information gathered from local neighborhood operators cannot recognize objects alone; it must be implemented by the specific knowledge about the geometrical shape of the objects. Thus model-based methods are developed.

Moreover, as it can provide more information than the monochrome image, color image has been used more and more frequently. Thus color image segmentation becomes more popular. Basically, color segmentation approaches are the application of monochrome segmentation approaches in different color spaces. A detailed description of color image segmentation techniques can be found in (Cheng, Jiang et al. 2001). The major monochrome image segmentation approaches, histogram thresholding, characteristic feature clustering, edge detection, region-based methods, fuzzy techniques, and neural networks, are discussed first in this paper. The descriptions, advantages, and disadvantages of the above methods are listed in Table 2.2. Then the color systems, RGB and the derivations, are reviewed.

Most monochrome segmentation techniques can be extended to color images with directly applying to each component of a color space, and then combining the results to obtain a final segmentation result. The problems of this simple extension are how to maintain the color information for each pixel, and how to choose the color representation for segmentation. There are no general algorithms and color space that are suitable for all color images and applications.
A segmentation algorithm that is a combination of edge detection approach and region-based approach is presented in (Devereux, Amable et al. 2004). This algorithm is designed for visible and near infrared data with the assumption that images consist of three basic components: segments, simple mixtures, and complex mixtures. Segments are clusters of at least four, non-aligned pixels with homogeneous radiometry. Simple mixtures are pixels between two neighbor segments with the combination radiometry of these two segments. Other pixels are complex mixtures. Edge detection starts with Gaussian smoothing of each image band and extraction of partial derivatives. Then multispectral slope approximation for each pixel is calculated. Finally local slope maxima are extracted. Following the edge detection, seed points are selected in the order of the seed size, or in the order of standard deviation of a particular size. Seed points are finally growing into segments using a recursive routine. The algorithm is tested with Landscape ETM for land cover parcels analysis. The human interpretation results are used as reference. There is just less than eighty percent correspondence between the reference and the test result. Most of the differences come from more detailed results generated from the segmentation algorithm.

Similar approach can be found in (Mueller, Segl et al. 2004). This kind edge and region based segmentation technique is developed for the extraction of large, man-made objects, especially agriculture fields, in high-resolution image. Edge extraction consists of three steps. First, edge candidates are extracted at multiple scales. Then edges of each scale are filtered with the criteria of strength, straightness, and length. The remaining edges are fused to the final edges. The following steps are edge-guided smoothing, edge-guided region growing, and region merging. The technique is tested with MOMS-02, IRS-C, IKONOS, and aerial imagery. The results of this technique are reported to be superior to those of mean shift algorithm and the software of eCognition.

Since the construction of roads, especially highways, railway, and dams will change the terrain, detecting these objects is necessary for this research. Many segmentation techniques can be used for automatic road extraction with depicting a binary image of the road network. The segmentation techniques are expected to be useful to cluster the elevation points in DTM, so as to find some distribution patterns.
Table 2.2  Monochrome image segmentation techniques (Cheng, Jiang et al. 2001)

<table>
<thead>
<tr>
<th>Segmentation technique</th>
<th>Method description</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
</table>
| Histogram thresholding      | Requires that the histogram of an image has a number of peaks, each corresponds to a region | It does not need prior information of the image. For a wide class of images satisfying the requirement, this method works very well with low computation complexity | (1) Does not work well for an image without any obvious peaks or with broad and flat valleys  
(2) Does not consider the spatial details, so cannot guarantee that the segmented regions are contiguous |
| Feature space clustering    | Assumes that each region in the image forms a separate cluster in the feature space. Can be generally broken into two steps: (1) categorize the points in the feature space into clusters; (2) map the clusters back to the spatial domain to form separate regions | Straightforward for classification and easy for implementation | (1) How to determine the number of clusters (known as cluster validity)  
(2) Features are often image dependent and how to select features so as to obtain satisfactory segmentation results remains unclear  
(3) Does not utilize spatial information |
| Region-based approaches     | Group pixels into homogeneous regions. Including region growing, region splitting, region merging or their combination | Work best when the region homogeneity criterion is easy to define. They are also more noise immune than edge detection approach | (1) Are by nature sequential and quite expensive both in computational time and memory  
(2) Region growing has inherent dependence on the selection of seed region and the order in which pixels and regions are examined  
(3) The resulting segments by region splitting appear too square due to the splitting scheme |
| Edge detection approaches   | Based on the detection of discontinuity, normally tries to locate points with more or less abrupt changes in gray level. Usually classified into two categories: sequential and parallel | Edge detecting technique is the way in which human perceives objects and works well for images having good contrast between regions | (1) Does not work well with images in which the edges are ill-defined or there are too many edges  
(2) It is not a trivial job to produce a closed curve or boundary  
(3) Less immune to noise than other techniques, e.g., thresholding and clustering |
| Fuzzy approaches            | Apply fuzzy operators, properties, mathematics, and inference rules (IF-THEN rules), provide a way to handle the uncertainty inherent in a variety of problems due to ambiguity rather than randomness | Fuzzy membership function can be used to represent the degree of some properties or linguistic phrase, and fuzzy IF-THEN rules can be used to perform approximate inference | (1) The determination of fuzzy membership is not a trivial job  
(2) The computation involved in fuzzy approaches could be intensive |
| Neural network approaches   | Using neural networks to perform classification or clustering | No need to write complicated programs. Can fully utilize the parallel nature of neural networks | (1) Training time is long  
(2) Initialization may affect the results  
(3) Overtraining should be avoided |


2.5  IKONOS stereo imagery

The IKONOS satellite, launched in September of 1999, provided global, accurate, high-resolution imagery to individuals, organizations, and governments for mapping, monitoring, and development. With the help of on-board position and attitude sensors, IKONOS stereo pairs can triangulate ground positions without using ground control points (GCPs) for exterior orientation. The flexible view capability enables to acquire stereo images of the same area on the same orbit pass with a time difference of 12 seconds (Figure 2.1). The orbit also provides 3-day revisit within 26° of nadir, and 141-day revisit within 1° of nadir. The performance features are listed in Table 2.3 (Dial, Bowen et al. 2003).

IKONOS imagery products are categorized to six levels: Geo, Standard Ortho, Reference, Pro, Precision, and PrecisionPlus. The categorization is according to positional accuracy, which is determined by the reliability of an object in the image to be within the specified accuracy of the actual location of the object on the ground. Geo Ortho Kit is a subset of the Geo product line. It is tailored for sophisticated users such as photogrammetrists who want to control the orthorectification process. The camera geometry obtained at the time of image collection is distributed together with the images. Geo Ortho Kit images can be used to produce highly accurate orthophotos with additional DTMs and GCPs. The products details are listed in Table 2.4, in which NMAS means the accuracy level can be related to U.S. National Map Accuracy Standards (Space Imaging 2004).

IKONOS Stereo imagery is available at one-meter resolution for the Reference and Precision accuracy levels. Rational polynomial coefficient (RPC) camera model file is provided with the stereo imagery pairs. It contains a series of coefficients to establish the nominal relationship from object space latitude, longitude, and height to images space line and samples. It is reported that the RPC camera model do not differ from the physical camera model by more than 0.04 pixel for all possible scenarios (Dial, Bowen et al. 2003). Image orientation for Precision and Reference Stereo images is
described by RPC data, while RPC coefficients for Precision Stereo images have been updated by use of ground control and so are more accurate.

Reference Stereo products have a horizontal accuracy of 25 meters CE90 and a vertical accuracy of 22 meters LE90; Precision Stereo products have a horizontal accuracy of 4 meters CE90 and a vertical accuracy of 5 meters LE90 (Space Imaging 2004).

Table 2.3 IKONOS performance summary (Dial, Bowen et al. 2003)

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orbit height</td>
<td>681 km</td>
</tr>
<tr>
<td>Orbit inclination</td>
<td>98.1°, sun synchronous</td>
</tr>
<tr>
<td>Descending node time</td>
<td>~10:30 a.m., local solar time</td>
</tr>
<tr>
<td>Field of regard</td>
<td>Up to 45° off nadir</td>
</tr>
<tr>
<td>Revisit time at mid-latitude</td>
<td>3 days at 60° elevation</td>
</tr>
<tr>
<td></td>
<td>11 days at 72° elevation</td>
</tr>
<tr>
<td></td>
<td>141 days at 89° elevation</td>
</tr>
<tr>
<td>Image sensors</td>
<td>Panchromatic and multispectral</td>
</tr>
<tr>
<td>Width of panchromatic arrays</td>
<td>13,816 pixels</td>
</tr>
<tr>
<td>Width of multispectral arrays</td>
<td>3454 pixels</td>
</tr>
<tr>
<td>Field of view</td>
<td>11 km at nadir</td>
</tr>
<tr>
<td>Minimum image length</td>
<td>11 km</td>
</tr>
<tr>
<td>Maximum mono image length</td>
<td>1000 km</td>
</tr>
<tr>
<td>Maximum stereo image length</td>
<td>400 km</td>
</tr>
<tr>
<td>Radiometric resolution</td>
<td>11 bits</td>
</tr>
<tr>
<td>Panchromatic ground sample distance</td>
<td>0.82 m at nadir</td>
</tr>
<tr>
<td>MTF at Nyquist</td>
<td>17%</td>
</tr>
<tr>
<td>Multispectral bands</td>
<td>Blue, Green, Red, NIR</td>
</tr>
<tr>
<td>Multispectral GSD</td>
<td>3.28 m at nadir</td>
</tr>
<tr>
<td>Blue bandpass</td>
<td>445 – 516 nm</td>
</tr>
<tr>
<td>Green bandpass</td>
<td>506 – 595 nm</td>
</tr>
<tr>
<td>Red bandpass</td>
<td>632 – 698 nm</td>
</tr>
<tr>
<td>NIR bandpass</td>
<td>757 – 853 nm</td>
</tr>
</tbody>
</table>

There is no problem of the image matching using IKONOS stereo pairs taken in the same orbit, as they have the identical scene content and lighting conditions. Due to the illumination change and the very high resolution, stereo pairs achieved by long time interval may cause large problems of the automatic image matching. In this case, Gauss-filter should be applied to smooth the image before matching (Jacobsen 2003).

A test was applied to check the accuracy of IKONOS stereo pairs processed without GCPs (Dial and Grodecki 2003). In this test, 24 IKONOS stereo pairs of different places were processed without GCPs. The positions of 49 GPS-surveyed checkpoints were measured in the stereo models, and compared with the coordinates of the GCPs. The calculated horizontal accuracy was 6.2 meters CE90 and vertical accuracy 10.1 meters LE90, relating to RMSE of 4.2 meters in horizontal and 6.4 meters in vertical. The maximum error of 49 checkpoints was 12 meters horizontal and 15 meters vertical.
Table 2.4 IKONOS product levels (Space Imaging 2004)

<table>
<thead>
<tr>
<th>Product</th>
<th>Positional Accuracy</th>
<th>Ortho Corrected</th>
<th>Target Elevation Angle</th>
<th>Mosaicked</th>
<th>Stereo Option</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geo</td>
<td>15.0 meters*</td>
<td>N/A</td>
<td>No</td>
<td>60° to 90°</td>
<td>No</td>
<td>Visual &amp; interpretive applications</td>
</tr>
<tr>
<td>Geo Ortho Kit</td>
<td>15.0 meters*</td>
<td>7.0</td>
<td>No</td>
<td>60° to 90°</td>
<td>No</td>
<td>Orthophoto production</td>
</tr>
<tr>
<td>Standard Ortho</td>
<td>50.0 meters**</td>
<td>25.0 meters</td>
<td>Yes</td>
<td>60° to 90°</td>
<td>No</td>
<td>Basic mapping projects</td>
</tr>
<tr>
<td>Reference</td>
<td>25.4 meters</td>
<td>11.8 meters</td>
<td>Yes</td>
<td>60° to 90°</td>
<td>Yes</td>
<td>Regional, large area mapping and general GIS applications</td>
</tr>
<tr>
<td>Pro</td>
<td>10.2 meters</td>
<td>4.8 meters</td>
<td>Yes</td>
<td>66° to 90°</td>
<td>Yes</td>
<td>Transportation, infrastructure, utilities planning, economic development</td>
</tr>
<tr>
<td>Precision</td>
<td>4.1 meters</td>
<td>1.9 meters</td>
<td>Yes</td>
<td>72° to 90°</td>
<td>Yes</td>
<td>High positional accuracy for urban applications</td>
</tr>
<tr>
<td>PrecisionPlus</td>
<td>2.0 meters</td>
<td>0.9 meters</td>
<td>Yes</td>
<td>75° to 90°</td>
<td>No</td>
<td>Detailed urban analysis, cadastral &amp; infrastructure mapping</td>
</tr>
</tbody>
</table>

* Exclusive of terrain effects
** May be up to 75 meters CE90 in undeveloped areas with high terrain relief (e.g., Andes or Himalayan mountain ranges)

The accuracy of DTM generated from IKONOS stereo images with GCPs is reported in (Kaczynski, Majde et al. 2004). IKONOS along-track Pan stereo images covering 80 square kilometres were used in this research. Thirty three well distributed natural GCPs measured with GPS were used as control points or check points for the orientation of the stereo images, after that DTM was generated from the images and the result was checked with the existing DTM, which was generated from 1:26000 scale aerial photos and filtered. The accuracies for three different terrain types, town, grassland, and hilly region, are 0.7, 1.3, and 2.0 meters respectively. After eliminating systematic errors, that accuracy was improved to 0.7, 0.5, and 0.7 meters. It is concluded to be compatible with the existing DTM generated from 1:26000 scale aerial photographs.

The DTM specifications in China are different with the resolution (scale), terrain types, and accuracy levels. There are three levels for every scale DTM. The specifications for the first level of the 1:10000 scale DTM are: vertical accuracy of 0.5 meters for the flat terrain, 1.2 meters for the broken terrain, 2.5 meters for the mountain terrain, and 5.0 meters for high mountain terrain. In the case of 1:50000 DTM, the appropriate accuracy specifications of the first level are 3 meters, 5 meters, 8 meters, and 14 meters. The specification for the third level is 2.0 times of the first level. In all cases, for the forest area, the accuracy specifications are relaxed to 1.5 times of original ones. From the above literature, it can be found that the DTM generated from IKONOS stereo images without GCPs is close to (a little more or less than) the third accuracy level of 1:50000 scale DTM, and the DTM generated from stereo images with well distributed GCPs can reach at least the same accuracy with the third level of 1:10000 scale DTM.
3. Detecting the need to update or upgrade DTM

After generating a new DTM from the stereo pair, the next concern is to check that the new DTM has a higher accuracy than the existing one. Is the accuracy of new DTM overall higher than the existing DTM, or only in some regions? Or in the worst situation, is the newly generated DTM worse than the existing one? The direct way should be working on the difference between these DTMs. It can quickly give the clues of the general differences between these two DTMs, and specific areas of big differences, thus help determine the lower accuracy regions either in old DTM or new DTM, or clues of the possible terrain change. To judge the difference between two DTMs, we must first estimate how accurate the two DTMs are.

3.1 Overall accuracy of DTM

The spectral analysis method allows us to estimate the internal accuracy of a DTM, under the assumption that we have detected and removed gross errors and systematic error, key influencing factor on accuracy is the sampling spacing, that is, the accuracy component related to the sampling spacing.

3.1.1 Spectral analysis and Fourier transform

Spectral analysis is a set of procedures to transform data from the spatial domain to the frequency, so that the data can be interpreted more easily on the basis of the inherent periodicities (Harrison and Lo 1996) and thus the terrain variability. In 1822, the French mathematician J. Fourier showed that any periodic function could be represented by an infinite series of sine and cosine waves. Many years later, he generalized this theorem to non-period function, and then periodic or non-periodic discrete time signals.

Fourier theorem and Fourier transform can be mathematically described as follows (Bendat and Piersol 1993).

For any periodic record \(x(t)\) of period \(T\),

\[
x(t) = x(t \pm kT) \quad \text{for} \quad k = 1, 2, 3, \ldots
\]

can be expanded in a Fourier series as
\[ x(t) = \frac{a_0}{2} + \sum_{k=1}^{\infty} (a_k \cos 2\pi f_k t + b_k \sin 2\pi f_k t) \]  
(3.2)

where

\[ a_0 = \frac{1}{T} \int_{0}^{T} x(t) dt = \mu, \]

\[ a_k = \frac{2}{T} \int_{0}^{T} x(t) \cos 2\pi f_k t dt \quad k = 1, 2, 3, \ldots \]

\[ b_k = \frac{2}{T} \int_{0}^{T} x(t) \sin 2\pi f_k t dt \quad k = 1, 2, 3, \ldots \]

\[ f_k = kf_i = \frac{k}{T} \quad k = 1, 2, 3, \ldots \]

\[ \mu \] is the mean value of \( x(t) \), \( f_k \) is the frequency of the wave components. The terms \( \{\mu, a_1, a_2, b_1, b_2\} \) are Fourier coefficients, which present the amplitude of each component.

Suppose \( x(t) \) is nonperiodic, the previous Fourier series can be extended as

\[ X(f) = \int_{-\infty}^{\infty} x(t) e^{-j2\pi ft} dt \quad -\infty < f < \infty \]  
(3.3)

on condition that

\[ \int_{-\infty}^{\infty} |x(t)| dt < \infty \]

the quantity \( X(f) \) defined by equation (3) is called the direct Fourier transform of \( x(t) \). Conversely, if \( X(f) \) is known, then \( x(t) \) can be induced by the inverse Fourier transform of \( X(f) \) with the formula

\[ x(t) = \int_{-\infty}^{\infty} X(f) e^{j2\pi ft} df \quad -\infty < t < \infty \]  
(3.4)

where \( j \) is the imaginary unit, \( x(t) \) and \( X(f) \) are called Fourier transform pairs.

In the field or laboratory \( x(t) \) can only be measured over finite time interval, and the condition for the Fourier transform can be always met, thus comes the concept of finite Fourier transform

\[ X_T(f) = X(f,T) = \int_{0}^{T} x(t) e^{-j2\pi ft} dt . \]  
(3.5)

When extended to two dimensional situation, the Fourier transform and inverse Fourier transform can be denoted as (Harrison and Lo 1996)

\[ X(k_1, k_2) = \sum_{t_1=0}^{n_1-1} \sum_{t_2=0}^{n_2-1} x(t_1, t_2) e^{-j2\pi((t_1/k_1)+(t_2/k_2))} \]  
(3.6)

\[ x(t_1, t_2) = \frac{1}{n_1n_2} \sum_{k_1=0}^{n_1-1} \sum_{k_2=0}^{n_2-1} X(k_1, k_2) e^{j2\pi((t_1/k_1)+(t_2/k_2))} \]  
(3.7)
where \( x(t_1, t_2) \) represents the sampled value at the coordinate \((t_1, t_2)\), the coordinate \((k_1, k_2)\) represents the frequency of the sinusoidal in the \((t_1, t_2)\) directions.

An important characteristic of the Fourier transform is that the reverse process is possible using the same procedure; it saves the computing capability greatly, especially after the invention of Fast Fourier Transform (FFT) algorithm in 1965. With FFT, the total amount of \((8N^2-14N+6)\) real multiplications and additions for \(N\)-total points being transformed can be reduced to \((5N\log_2N-6N+6)\) \((\text{Harrison and Lo 1996})\).

### 3.1.2 DTM accuracy estimated with spectral analysis

The application of Fourier analysis to terrain analysis can be dated back to the late 1960s \((\text{Harrison and Lo 1996})\). The advantage of analysing in the frequency domain is that the relationship between the systems input and output is defined by a multiplication instead of the convolution in the spatial domain \((\text{Tempfli 1980})\). In addition to its saving on calculation, Fourier transform does provide information which is not available in spatial domain. Spectral analysis is used to describe the terrain relief and to estimate the accuracy of DTM without the need for checkpoints \((\text{Tempfli 1980}; \text{Tempfli 1999})\). It is tested that in the worst-case 1000 checkpoints are needed for an area of \(8 \times 12 \text{ km}^2\) to attain the same RMSE tolerance, 10 percent, with spectral analysis \((\text{Tempfli 1999})\).

The spectral analysis for DTM accuracy estimation proposed in the above papers can be briefly described as follows.

The surface described by DTM, \( \hat{z} = \hat{f}(x, y) \), is only an approximation of the genuine terrain surface \( z = f(x, y) \). The variance of the DTM error is defined as

\[
e(x, y) = f(x, y) - \hat{f}(x, y)
\]

\[
\sigma^2 = \frac{1}{LX \cdot LY} \int_0^{LY} \int_0^{LX} e(x, y)^2 \, dx \, dy
\]

In practice, the genuine terrain surface is not known, thus the variance between the estimated and genuine terrain cannot be calculated. RMSE is the commonly used estimator of the variance. It is calculated with the difference between the elevation value of checkpoints and the corresponding elevation value in the DTM as following.

\[
\hat{\sigma} = \sqrt{\frac{\sum (Z_i - \hat{Z}_i)^2}{n}}
\]

In case that the checkpoints are not available, the error of sampling, measuring, and interpolation in conventional DTM generation method, can be simply estimated with spectral analysis as follows.
\[
\sigma^2 = \sigma_s^2 + \sigma_r^2
\]
\[
\hat{\sigma}_s^2 = 2 \sum_{k=1}^{N/2} \{1 - H(v_k \Delta x)\}^2 |F(v_k)|^2
\]
\[
\hat{\sigma}_r^2 = 2 \hat{\sigma}_m^2 \int_0^{1 \Delta x} H(u) du \quad u = v \Delta x
\] (3.10)

where \(\hat{\sigma}_s\) is the influence of sampling and interpolation, \(\hat{\sigma}_r\) is the influence of the measuring error, \(H(u)\) is the transfer function of the interpolation method, \(|F(v_k)|\) is the amplitude spectrum, obtained by the Fourier transform of a profile, \(\Delta x\) is the sampling interval, \(v\) is the frequency of a sinewave as described by the amplitude spectrum.

### 3.2 Critical regions delineation

Automatic image matching cannot acquire good results in the road and other surfaces with no or little texture, and the measuring error is likely to be large in the steep slope area. In the forest and urban area, lots of matching points are on the top of vegetation or buildings instead of bare ground, thus DTM cannot be attained without further analysis and processing. On the other hand, terrain change may happen in the steep slope area, such as landslide. Due to human activities, road and dam construction also change the terrain. To update the existing DTM, differentiate change from errors included in the DTMs, more attention should be paid to these areas. Steep slope areas can be delineated from the existing DTM, while the road, forest, and urban areas can be extracted from the remote sensing imagery.

#### 3.2.1 Steep slope area delineation

Slope gradient and orientation are important controls in a number of surface processes. Several algorithms have been developed to calculate the gradient of the surface from DTM. However, most methods are based on the concept of “moving window” with a 3x3 kernel. They have the advantage of minimizing the effect of data errors in general. The disadvantages are that the computed slope values are not so accurate; they are the slopes for an equivalent area of up to twice the cell size. Especially in the case of rough terrain and coarse resolution grids, the slopes are always underestimated. A vector algebra algorithms for calculating the gradient of the surface is presented in (Corripio 2003). It uses the nearest four neighbor points, that is, four points of the minimum area unit in a DTM, to calculate the gradient. Though it is not as accurate as calculating with the triangular mesh in DTM, it keeps the cell as the surface area unit, which is necessary for a lot of raster operations. Furthermore, it takes advantages of the array handling power of modern programming languages, such as Matlab, thus can be implemented very efficiently.

The method can be described as follows. In a regular square grid of cell size \(l\), a point at row \(i\) and column \(j\), its elevation value is denoted as \(Z_{i,j}\), the same denotation for the other three nearest points (Figure 3.1). The \(x\), \(y\), \(z\) components of the vectors along the side of the grid cell are defined as:
Figure 3.1 Vector normal to a grid cell surface. Vector \( \mathbf{n} \) is the average of cross products \( \mathbf{a} \times \mathbf{b} \) and \( \mathbf{c} \times \mathbf{d} \). Its length approximates the surface area of the grid cell with accuracy depending on resolution (Corripio 2003).

The vector normal to the grid cell \( \mathbf{n} \) can be approximated as the average of the two normal vectors of the triangle along the diagonal.

\[
\mathbf{n} = \frac{\mathbf{a} \times \mathbf{b}}{2} + \frac{\mathbf{c} \times \mathbf{d}}{2} = \begin{pmatrix} \mathbf{i} & \mathbf{j} & \mathbf{k} \\ \mathbf{i} & \mathbf{j} & \mathbf{k} \end{pmatrix} + \begin{pmatrix} \mathbf{i} & \mathbf{j} & \mathbf{k} \\ \mathbf{i} & \mathbf{j} & \mathbf{k} \end{pmatrix}
\]

(3.12)

Simplifying the Equation (3.12) and substituting the appropriate vectors with grid elevation points and cell spacing in Equation (3.11), the vector normal to the grid surface can be denoted as:

\[
\mathbf{n} = 0.5l(z_{i,j} - z_{i+1,j} + z_{i,j+1} - z_{i+1,j+1}), 0.5l(z_{i,j} + z_{i+1,j} - z_{i,j+1} - z_{i+1,j+1}), l^2 \}
\]

(3.13)

The surface area of this cell is \( |\mathbf{n}| \), and the unit vector in the direction of \( \mathbf{n} \) is denoted as \( \mathbf{n}_u \). The slope \( \zeta \) can be calculated with the equation of

\[
\zeta = \cos^{-1} n_{uz}
\]

(3.14)

where \( n_{uz} \) is the z coordinate of vector \( \mathbf{n}_u \).
Many factors affect the happening of landslide, such as the angle of slope, the water content, the type of earth material involved, and local environmental factors such as ground temperature. Research on the mean slope angle frequency distribution has been carried out by (Iwahashi, Watanabe et al. 2003). From the statistics on more than 1000 happened landslides in a mudstone area, it is found that a landslide happens with 90 percent probability when the mean slope angle is larger than 20°, and 50 percent for an average angle of 14°. So it is reasonable to select 14° as the threshold for slope angle when delineating the steep slope areas. In steep slopes, we can or have to tolerate larger differences between the old and new DTM than in flat terrain.

3.2.2 Road region delineation

The construction of a road, especially a highway, will change the terrain obviously, as the road is normally higher than the ground. Along country roads and rivers, if there is vegetation, the DTM generated from image matching will contain non-ground points if not properly filtered. The differences of these areas between the old and new DTM will be larger than what we can expect from measuring error and sampling spacing.

Finding new roads is valuable to this research, because along new roads we expect terrain relief changes. Thus the road extraction from satellite images is needed. In order to find old roads and explain possible big differences in the DTM along them, the existing topographic map or database is needed. A lot of researches have been done already on road extraction and different techniques have been investigated and proposed. In (Mena 2003), a detailed summary is made on the techniques and status of automatic road extraction for GIS update from aerial and satellite imagery, based on nearly 250 references related with this topic. It classifies the surveys and different techniques according to three factors: the present objective, the extraction technique applied, and the type of sensor utilized. Some of the techniques summarized in this article are morphology and filtrate, segmentation and classification, multi-scale and multi-resolution, knowledge representation and fuzzy modelling.

In order to detect the terrain change in road, a buffer along the road should be established. Assuming the width of the road is 15 meters, somehow a reasonable width value, when the grid size of the DTM is 25 meters, at most one point can be located on the road surface in the across direction. In this case, a buffer of 50 meters along both sides of the road should be established. In the road buffer, if the differences between these two DTMs are big and some regions are filled and some regions are cut, it is a pattern of road construction. It can be concluded that this big difference is caused by terrain change because of road construction.

3.2.3 Urban and forest region delineation

Urban and forest regions affect the quality of DTM generated from the images, similar to vegetation along the road. When we compare the newly generated DTM with the old one, we may get differences in these regions in the order of the heights of the buildings and vegetation. So it is necessary to delineate the regions of urban and forest before drawing a conclusion on change or error happening in these areas.
Urban and forest regions can be delineated based on the spectral information of images, such as Normalized Difference Vegetation Index (NDVI). The existing topographic data is another useful information for the urban and forest delineation.

Once we have delineated forest areas, we may be able to get further clues from analysing the amplitude spectra of these areas. If an amplitude spectrum shows variation in the high frequency range, we can suspect that some matching points are on the top of vegetation, while other points are on the ground. If the amplitude spectrum variance is low and most of the amplitudes are close to zero, it tells that the matching points are on the top of vegetation, thus the conclusion of dense forest can be drawn. Similarly we can analyze urban areas to get a hint on the effectiveness of DSM filtering that has been applied.

3.2.4 Identifying and possibly correcting inaccurate regions in old DTM

Delineating the inaccurate regions in existing DTM ahead will benefit the discrimination of real change from error included in the DTM. It will be based on the correlation between the point under investigated and its neighbors. Similar method can be found in (López 2000).

3.2.5 Identifying and possibly correcting inaccurate regions in new DTM

Since the automatic image matching can not work well in the areas of poor texture in addition to steep slope, some image processing software will report “bad matching” in the form of a quality map. It is helpful information for detecting terrain changes and errors in the DTMs.

In some software, such as LPS, this kind of point will be reported as suspicious point, and its elevation will be substituted with the interpolated elevation from its neighbors. If the used image processing software do not substitute the elevation of the “bad matching” point, it is necessary to carry out the interpolation processing. It can be done with the following method. First, compare the new, possibly bad elevation in the new DTM with the one from the old DTM, then compare the interpolated elevation in the new DTM instead of the measured one with the one from the old DTM. If the interpolated elevation gives smaller difference with the existing DTM than the measured one, the elevation of the bad matching point can be substituted with the interpolation elevation.

3.3 Accuracy measures identification

To compare the accuracy of these two periods of DTMs and decide whether to update or upgrade the old one or not, suitable accuracy measures are required.
3.3.1 RMSE and mean error

RMSE can be calculated with Equation (3.9) with checkpoints that at least one order better than the old DTM. Though the RMSE is effective and generally used, due to the defects described in the related literature, it is not suitable to act as the accuracy measure alone. Besides, it will hide the big differences at some points by dividing the differences with the total amounts of the investigated points.

Due to some defects of DTM production method or production procedure, systematic error will be introduced to the resulting DTM. It will cause DTM to deviate the true value in a systematic way and in a predictable magnitude. The accuracy measure for detecting systematic error should be used. The mean error is the simplest candidate. It can be calculated from the average elevation difference between DTM and checkpoints. However, if the mean error is calculated for the whole study area, it will loose its function as systematic error indicator, as it may be reduced to undetectable level with the average by the whole. Mean error of suspicious region is really needed. Analysing the autocorrelation of the difference between these two DTMs could be of further help in detecting systematic errors.

3.3.2 Variance of the difference between two DTMs

Some other quality measures can be acquired through the analysis of the difference between these two DTMs. Assume that the old DTM and the new DTM have the same dimensions, say $m$ rows by $n$ columns, the difference between these two DTMs can be denoted with

\[ \text{dif} = DTM_{\text{Old}} - DTM_{\text{New}} \]  

(3.15)

the variance of \( \text{dif} \) is

\[ \sigma^2_d = \frac{1}{m \times n} \sum_{i=1}^{m} \sum_{j=1}^{n} (\text{dif}_{ij} - \mu_d)^2 \]  

(3.16)

where

\[ \mu_d = \frac{1}{m \times n} \sum_{i=1}^{m} \sum_{j=1}^{n} \text{dif}_{ij} \]  

(3.17)

\( \mu_d \) is the mean difference, it corresponds to the mean error described in section 3.3.1 if one of the two DTMs takes the role of the checkpoints.

According to the error propagation law, the variance of \( \text{dif} \) can be also estimated with the variances of old DTM and new DTM as

\[ \hat{\sigma}^2_d = \hat{\sigma}^2_{\text{Old}} + \hat{\sigma}^2_{\text{New}} \]  

(3.18)
where $\hat{\sigma}_{Old}^2$ is the variance of the old DTM, and $\hat{\sigma}_{New}^2$ is the variance of the new DTM. They can be estimated with spectral analysis according to Equation (3.10) as

\[
\hat{\sigma}_{Old}^2 = \hat{\sigma}_{OS}^2 + \hat{\sigma}_{OR}^2
\]

\[
\hat{\sigma}_{New}^2 = \hat{\sigma}_{NS}^2 + \hat{\sigma}_{NR}^2
\]

where $\hat{\sigma}_{OS}$ is the influence of sampling and interpolation to the old DTM, $\hat{\sigma}_{OR}$ is the measuring error in the old DTM, $\hat{\sigma}_{NS}$ is the influence of sampling and interpolation to the new DTM, and $\hat{\sigma}_{NR}$ is the measuring error in the new DTM. In the following, $\hat{\sigma}_d$ is called as standard deviation.

Averaging effect will happen on the variance calculated with checkpoints, since the whole area will average some big differences. By spectral analysis the variance of the DTM can be estimated, specifically only the accuracy component conditional on sampling density. The largest error will appear there where terrain is rough. In this sense there is no averaging over the entire area but the worst-case estimate, which is the expectation of the method with spectral analysis. Thus the $\hat{\sigma}_S$ from spectral analysis is valid for the entire area, but in the sense of giving an estimate for the worst region. In smooth areas the DTM error will be lower.

If the measuring error ($\hat{\sigma}_R$) is added to the accuracy estimate of spectral analysis, the averaging effect will happen because $\hat{\sigma}_R$ can be different in regions, for example, it will be larger in areas of low texture and steep slope.

When analyze the difference between the two DTMs, it becomes tricky to relate variance $\sigma_d^2$ with $\sigma_d^2$. The averaging effect may happen in the variance $\sigma_d^2$ over the large area. But the variances estimated with spectral analysis of the old DTM $\hat{\sigma}_{Old}^2$ and new DTM $\hat{\sigma}_{New}^2$ are not affected by averaging, unless the dominating component in $\hat{\sigma}_{Old}^2$ and $\hat{\sigma}_{New}^2$ is the measuring error influence $\hat{\sigma}_R$. Thus the calculated variance $\hat{\sigma}_d^2$ should be smaller than the estimated variance $\hat{\sigma}_d^2$. If $\sigma_d^2$ is larger than $\hat{\sigma}_d^2$, a change or significant error can be suspected.

### 3.3.3 Maximum difference threshold

If values in $\text{dif}$ are normally distributed, a difference value larger than three times of $\hat{\sigma}_d$ is a “near uncertainty error” and if such errors are clustered there must be change of terrain relief or local systematic error. So the factor of $3\hat{\sigma}_d$ can be used as an indicator of error or change for specific regions.
3.4 Blunder elimination

Mismatching and some operator or machine errors cause blunders. Some methods on eliminating blunders were reported by (López 2000). As blunder can be regarded as instant high frequencies, they can be differentiated from long lasting low frequencies of terrain variance. It means spectral analysis may be useful in eliminating the blunders. The similar method is used for terrain analysis (Harrison and Lo 1996) and to filter airborne laser scanner data (Marmol and Jachimski 2004).

In (Harrison and Lo 1996), the terrain is replaced by residuals by removing the surface trend, thus makes it apparent of the variance associated with periodic trends. After that, two-dimensional FFT is applied to transfer the data processing from spatial domain to frequency domain. Among the output wave sets, only those meet the thresholds of power inclusion and contribution ratios are remained for terrain reconstruction, which is through inverse Fourier transform.

The general concept used in (Marmol and Jachimski 2004) is that the low frequencies are the run of topographic surface, while the high frequencies are caused by the field objects, and the fact of filtering is designing a low-pass filter, which lets the lower frequencies pass and blocks the higher frequencies. Before applying FFT, surface trend is removed through subtracting the fitted surface determined with polynomial function. Then a digital filter is designed with window method. FFT is then used to determine the cut-off frequency. The danger of this approach is that not only “field objects” are filtered out but also terrain relief features of similar dimensions.

3.5 Analysis of small difference

For the whole region of difference between two DTMs, the variance of the difference can be calculated with Equation (3.16) or estimated with Equation (3.18), and the maximum and minimum differences can be easily found. As discussed in section 3.3, for the difference between two DTMs, the calculated variance \( \sigma^2_d \) should be smaller than the estimated variance \( \hat{\sigma}_d^2 \). On the other hand, the absolute value of difference \( \text{dif}_{ij} \) should be smaller than the maximum difference threshold \( 3\hat{\sigma}_d \), providing that the difference is normally distributed.

If both conditions are met, it is likely that no terrain change has happened in this area larger than tolerated by the accuracy specifications. We only need to compare the global accuracy estimates. If the estimate of the new DTM is less than the old DTM, it denotes that the new DTM has a higher accuracy than the old DTM related to sampling density and measuring precision. Unless the area was covered by forest with a closed tree canopy and the new DTM is an unfiltered DSM, we can simply upgrade the whole old DTM with the new DTM.

Assuming that an area in both DTMs is not well filtered, there is a possibility that the difference between them is too small to detect this error. To avoid its happening, we can filter build up area and
vegetation area that can be extracted from the satellite images, and then compare the filtered DTM with the old DTM. If the filtered DTM has a higher accuracy than the old one, we can upgrade the old DTM with the new filtered DTM.

3.6 Analysis of big difference

When one of the conditions discussed in the above section is not met, it is possible that terrain change might have happened in this area. Since the existing DTM had been checked when it was produced and some blunders in the old and new DTMs could be eliminated or reduced with the methods discussed before, the remaining defects included in the DTMs should be the effects of buildings and vegetation, some random errors, and terrain relief change. We mainly concern the terrain change and the effects of buildings and vegetation. Once we can make sure that the big difference is coming from terrain relief change or poor filtering in the old DTM, we can update or upgrade the corresponding regions in the old DTM with the new DTM. If the reason for big difference is testified as poor filtering in new DTM, we have to apply effective filtering on the new DTM and update or upgrade the old DTM afterwards, or leave this region for human checking.

Due to the reasons discussed before, special attentions should be paid to the regions of road buffer, urban, forest, and steep slope. For every critical region, the variance of the difference between two DTMs can be calculated and estimated. The maximum and minimum difference values can be found too. The big difference happening region can be located with the discriminant discussed before. The following analysis is for such regions with big differences.

3.6.1 Road buffer regions

If the big differences along the road buffer can be clustered to form a pattern of cutting and filling, it is likely that the big differences come from the road construction. The elevation values of these regions can be updated with the values in the new DTM.

If the pattern of cutting and filling does not exist, the mean difference is negative and its absolute value is within certain range of vegetation height, then it can be deemed that the big differences are the effects of vegetation contained in the new DTM. For such regions, effective filtering is necessary. Otherwise, they have to be delineated and checked by the operator. In contrast, if the mean difference is positive and other conditions are the same, it can be thought as poor filtering in the old DTM. The elevations of these regions can be upgraded with those in the new DTM.
3.6.2 Urban and forest regions

For the urban and forest regions, the big differences may result from poor filtering. There are four possibilities: urban area are not well filtered in the old DTM, urban area are not well filtered in the new DTM, forest area are not well filtered in the old DTM, and forest area are not well filtered in the new DTM. When compare the difference between two DTMs, the relative filtering effects may cause problems. For example, the old DTM and the new DTM in the urban area are both not well filtered, but the old DTM may be affected by the poor filtering much than the new DTM, or may be affected less than the new DTM, and the effects of filtering may or may not be reflected in the DTM difference. It makes the problem much more complex.

To solve the problem, there are two options, one is applying effective filtering, and another is evaluating the effects of the previous filtering work with suitable tools or methods. Spectral analysis is a promising method; the appropriate explanation is described in section 3.2.3.

When the filtering effects on the DTM are determined, the analysis for the big differences in the urban and forest regions is simpler than before. In the case that the urban or forest area is not well filtered only in the old DTM, the mean difference will be positive. The effects of buildings or vegetation cause the big differences in this region, and the elevation values of this region can be upgraded with the new DTM. In the case that these areas are not well filtered only in the new DTM, the effects of building and vegetation cause the big differences too. The mean difference will be negative, and new DTM have to be applied effective filtering before upgrading the old DTM.

The worst situation is that these areas are not well filtered both in the old DTM and in the new DTM, and the difference between them is not big enough to detect. To avoid its happening, we can filter build up area and vegetation area that can be extracted from the satellite images, and then compare the filtered DTM with the old DTM. If the filtered DTM has a higher accuracy than the old one, we can upgrade the old DTM with the new filtered DTM.

3.6.3 Steep slope regions

In the steep slope region, segment the big differences and look for clusters of large difference in one direction. If there is a cut in the new DTM uphill of a steep slope area and a fill downhill, it is the pattern of cutting and filling, we can say there is a terrain change happening in this steep region. Thus the elevation values of this region can be updated with the new DTM.

The case of changes in the terrain overlaid with large measuring error by image matching is likely to occur particularly in landslide areas. If this case is suspected, it may help to filter the surface model $\text{diff}$ in order to reduce a random component by the amount $\hat{\sigma}_R$ which has been introduced in the global accuracy assessment before.
3.7 Suggested workflow for DTM updating

The general steps to update the existing DTM with high resolution satellite images can be briefly described as follows and depicted in Figure 3.2.

- Generate new DTM from the images using automatic image matching method.

- Detect and eliminate or reduce the systematic error, gross error possibly contained in the old DTM and new DTM. The related methods are discussed in section 2.2, 3.2, and 3.4.

- Estimate the accuracy of two DTMs with the technique of spectral analysis to get the global accuracy estimates, through which an impression on the quality related to sampling of these DTMs can be attained.

- Delineate the steep slope areas from the existing DTM, as well as urban, forest, roads, and railway from the satellite images.

- Calculate the accuracy measures of the critical regions from the difference of these two DTMs. They can be used to detect the terrain change and the effects of buildings and vegetation.

- If there is no big difference found from the accuracy measures and the new DTM has a smaller global accuracy estimated with spectral analysis than the old DTM, the old DTM can be upgraded with the new DTM.

- If big difference is found, analyze the reason of the big difference as described in section 3.6. According to different situation to update or upgrade the old DTM, or filtering the new DTM. Otherwise, it can be left to human check. There are two possible methods for this check, one is visual check by stereo overlay, and another is check by left-right orthophoto method.

- The filtered DTM should be checked once more to ensure the quality of the processing.
Figure 3.2 Global workflow of the DTM updating with high resolution satellite images
4. Tests with an existing DTM

4.1 Test data

As shown in the last chapter that DTM updating with high resolution satellite images is a very complex issue that includes automatic feature extraction, DSM filtering, systematic error and gross error detection and elimination, and accuracy analysis. This research develops tools and experimentally tests several concepts aiming at automatically updating and upgrading a “medium scale” DTM with a new primary data of IKONOS images. Firstly DTM is generated from the stereo pairs by automatic image matching, then the information contained in the images and existing DTM are used to help in finding the error prone area and change prone area.

Since SBSM of China is planning to update the geospatial database at the scale of 1:50000 and 1:10000, it is valuable to find an economic and feasible update solution for DTM. So it is decided to select an area in China as the study area, and use the Chinese data as the test data.

4.1.1 Ideal study area

In order to differentiate real terrain change from errors contained in existing DTM and uncertainty coming from the satellite images, and to test the effectiveness of the proposed methods on different terrain types, the study area should meet with the following requirements:

- The area should contain plain, mountain, and urban region;
- There should be some terrain changes happening there, such as landslide; or
- There should be some constructions, such as railway, highway, and dam.

4.1.2 Ideal test data

The ideal test data should include the following contents.

- IKONOS stereo pairs with RPC file

DTM will be generated from the stereo pairs, and RPC file is necessary to rectify the orientation of the stereo images.

To delineate road, forest, and urban area automatically, multi spectral imagery is useful.
• Existing DTM and meta data file

The existing DTM is useful for slope information extraction and supplying reference information through subtraction. It is assumed but not necessarily to be generated from digitized contour lines. The meta data of the DTM is needed to determine the lineage, grid size, planar coordinate system, and height reference system applied in this DTM. The newly generated DTM should adopt the same systems; otherwise two DTMs are not able to be horizontally georeferenced and vertically compared.

• Image control points

To improve the elevation accuracy of the newly generated DTM, control points that can be clearly discerned in the images are needed. These points should have both accurate horizontal and vertical coordinates. They are used to rectify the orientation with RPC file and control the elevation accuracy. As discussed in section 2.5, the accuracy of the DTM extracted from IKONOS stereo images without control points can not completely meet with the accuracy requirement of 1:50000 scale DTM. It is necessary to use control points to improve the elevation accuracy.

• Coordinate system transformation parameters

The IKONOS images adopt WGS 1984 coordinate system. Almost every country has its own national coordinate system for topographic databases. In China, two planar coordinates exist simultaneously; they are Beijing 1954 coordinate system and Xian 1980 coordinate system. In order to update the existing DTM, coordinate transformation is necessary.

Different coordinate systems may have different ellipsoids, datums, and projection categories. Coordinate transformation between different ellipsoids is mathematically accurate; the most accurate model for transformation applies seven parameters, including three displacement parameters, three rotation parameters, and one scale parameter. Parameters for transforming from ellipsoid to datum are determined by geodetic surveying. When transforming geospatial coordinates to coordinates in a map projection system we have to cope with different projection zones if the country is large. In the same datum, transformation between different projections is mathematic processing.

For an application within a small area, the transformation parameters can be calculated with at least three points whose coordinates in two systems are known, an extra point is used to check the accuracy of the transformation.

Apart from the planar coordinates related with specific ellipsoid, height above the ellipsoid surface is always needed to substitute with height above geoid to maintain the physical meaning of height. Geoid undulations can be used in the height correction; however, it is not available or not sufficiently accurate everywhere. In practice, method of local fitting to vertical control points is adopted. Thus the elevation control points are also required.
4.1.3 Available data and the related tests

Perfect data that meet all the requirements are not usual, especially for the classified and sensitive data. The availability of such data brings big difficulties in this research on testing the developed concepts and causes a lot of time delay.

IKONOS Pan stereo pairs with RPC file of an area in China are available, as well as a topographic map of 1:50000 scale produced in 1980’s and a piece of 1:50000 DTM generated from the topographic maps of the same area. The DTM adopts Xian 1980 coordinate system and has the grid size of 25 meters. These are the only available data. Unfortunately, the other data, such as the image control points and coordinate transformation parameters, are not available, although they are necessary for the tests.

The tests on the Chinese data include: generate DTM from the IKONOS stereo images, subtract the newly generated DTM from the existing DTM, estimate the accuracy of the old DTM and new DTM with spectral analysis method, and check the accuracy of two DTMs with checkpoints. The test results and analyses on these data are presented in the following section of this chapter.

After extensive efforts to obtain and utilize the data from China, we had to conclude that it is necessary to look for substitute data source. Another available data are aerial photographs and some control points of Moers in Germany. Old DTM of this area is not available. Finally the contour lines of the selected study area are acquired from a German organization. It is designed to use these contour lines to generate a DTM using as the old DTM. However, these raster format contour lines are dashed lines without coordinates. We overlapped the contour images on the orthophoto and tried to vectorize these contour lines automatically in ArcGIS. With appropriate parameter settings, the contour lines can be vectorized well, but the elevation labels are also vectorized and some closed contour lines are linked together. Apparently, a lot of editing is needed and the elevation value of every line has to be designated. Besides, contour lines of the hill and the railway area are not included in the raster image. The contingency plan was to experimentally investigate error detection. A DSM was generated from the aerial photographs. Due to the large scale (1:3500) of the photos, the effects of buildings and vegetation are prominent in the DSM. A kind of knowledge-based filtering processing is carried out to remove the effects of buildings and vegetation. The discriminant for change and poor filtering discussed in Chapter 3 is tested with the unfiltered DSM and filtered DSM. The related work is presented in Chapter 5 and Chapter 6.

Aerial photos of the Tessina landslide area, as discussed in (van Westen and Lulie Getahun 2003), were kindly offered by Dr. van Westen. We intended to test the concept of change detection with this landslide case. However, the photograph parameters and the control points are not available. It is difficult to generate a DTM accurately with these photographs and thus difficult to test our concepts of change detection. The test of change detection on real terrain relief change is not carried out.
4.2 DTM extraction from IKONOS stereo pairs

Leica Photogrammetry Suit (LPS) is used to generate DTM from the IKONOS stereo images. Specific regions can be digitized to include or exclude in DTM generation. Furthermore, different regions adopt different extraction strategies. The default search size is 21×3, a correlation size of 7×7, and a coefficient limit of 0.8. Search size is the search window size in pixels to search for the corresponding image points appearing within the overlapping area of the left and right images. Correlation size is the window size used for computing the correlation coefficient between the stereo images. Correlation limit is the minimum correlation value for accepting a pair of points as matching candidates. According to the terrain type settings, different parameters are applied. These terrain types include high mountains, middle mountains, low mountains, rolling hills, flat areas, high urban, low urban, and forest. DTM filtering is also available. There are four levels of filtering: high, moderate, low, and none, which are used to control the smoothing of spikes and pits in the data.

In the production of DTM, the DTM point status image can be designed as one output. The point status is about the correlation value of this point in automatic image matching, and it can have a value of excellent, good, fair, isolated, or suspicious. The correlation value of excellent point is between 1 and 0.85, good for values between 0.85 and 0.7, and fair for values between 0.7 and 0.5. Isolated points are those that do not have immediate neighbors. For a specific point, the difference between the original elevation value and the value interpolated from its eight neighbors can be calculated. If the difference is three times more than the standard deviation of the eight neighbors’ elevation values, the point is considered as suspicious and its elevation is substituted with the interpolated elevation.

In this research, the orientation of the IKONOS images is carried out with the RPC file alone, since GCPs are not available. The coordinate system for the generated DTM is set to WGS 1984 geographic coordinate system, and then reprojected to Beijing 1954 coordinate system, as it is available in the used Erdas software. The resolution of the newly generated DTM is 10 meters. An area of 500 rows by 500 columns is selected as the study area. The IKONOS image of the study area is shown in Figure 4.1. This area includes large amounts of plain, some hills covered with vegetation, some urban areas, some water bodies, and some roads. The elevation values change from 40 meters to 420 meters. The extracted DTM is shown in Figure 4.2. From this figure, the building clusters, such as the stadium beside the river, and some bridges still can be discerned.
Figure 4.1 The IKONOS image of the study area

Figure 4.2 DTM generated from IKONOS in the grid size of 10 meters
4.3 Difference between two DTMs

In this area, DTM with the scale of 1:50000 is available. It uses Xian 1980 coordinate system, and it is in the grid size of 25 meters. The newly generated DTM is in Beijing 1954 coordinate system. To compute the difference between the existing DTM and the new DTM, they should be referenced to the same coordinate system. The coordinate transforming parameters between Xian 1980 and Beijing 1954, or some control points with the coordinates of both systems, are needed. Unfortunately, neither of them is available.

To get general impression of the difference between these two DTMs, they are matched with the coordinates of lower left corner, though it is known to be in low accuracy. The difference between them was calculated at the resolution of 10-meter and 25-meter. At 10-meter resolution, the maximum difference is 126.40 meters, and the minimum difference is -128.17 meters. The mean difference is relatively small, -3.68 meters, with a standard deviation of 15.92 meters. The similar situation is with the result calculated at 25-meter resolution. The statistics are tabulated in Table 4.1. The difference image is shown in Figure 4.3, and the histogram of the difference is shown in Figure 4.4. From the difference figure, comparing with Figure 4.1 of the IKONOS image, it can be seen that happening in the plain area are mainly small differences, and the big differences happen in the hilly area. The histogram shows a symmetric distribution similar to a Gaussian (normal) distribution. Thus the theorem about the maximum difference threshold discussed in Chapter 3 is reasonable.

As mentioned in section 2.5, the accuracy of the third level “1:50000 scale DTM” is 10 meters for the broken terrain, accuracy for the plain terrain is less than 10 meters. According to (Dial and Grodecki 2003), the DTM extracted from IKONOS stereo images without control point can reach the vertical accuracy of 6.4 meters. If we use the accuracy indicator for the broken terrain, the standard deviation of the difference can be calculated with Equation (3.18) as 11.9 meters, and the maximum difference threshold should be three times of the standard deviation as 35.7 meters. However, the calculated standard deviation is 15.92 meters, the absolute value of both the maximum and the minimum differences are more than 120 meters. The effects of poor forests filtering will not cause a big difference like this. Since we have not carried out gross error and systematic error eliminating processing, we cannot say it is because of the change and poor filtering. From the Figure 4.3, it can be seen that in the hill area a region of positive difference is next to a region of negative difference, and the segments of these regions do not look like landslide or cut and fill along a highway. The reason for big difference should be poor horizontal matching.

<table>
<thead>
<tr>
<th></th>
<th>10-meter resolution</th>
<th>25-meter resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max</td>
<td>126.40</td>
<td>128.50</td>
</tr>
<tr>
<td>Min</td>
<td>-128.17</td>
<td>-120.20</td>
</tr>
<tr>
<td>Mean</td>
<td>-3.68</td>
<td>-3.94</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>15.92</td>
<td>15.83</td>
</tr>
</tbody>
</table>

Table 4.1 Statistics of differences between old DTM and IKONOS DTM
Figure 4.3 The difference between the old DTM and new DTM

Figure 4.4 Histogram of the difference between two DTMs
4.4 Accuracy estimated with spectral analysis

Spectral analysis is used to estimate the accuracy of the existing DTM and the IKONOS DTM with Equation (3.10) assuming a measuring error of 0.5 meters. Six profiles as shown in Figure 4.5 are extracted to apply the spectral analysis. Before the Fourier transforming, the extracted profiles are levelled to avoid the saw-teeth effects. Big difference of accuracy estimation happens in profile C, which is located in the bottom of the DTM with high variation of elevation. This profile and its Fourier Transform amplitude are plotted in Figure 4.6.

The calculated accuracies are listed in Table 4.2. The accuracy of the old DTM is estimated to be 0.53 meters with the standard deviation of 0.17 meters, while the accuracy of new DTM is 0.47 meters with the standard deviation of 0.03 meters. In this sense, new DTM has higher accuracy than the old DTM. However, this method used here assumes that the systematic error and gross error are removed. That means that the effects of systematic errors and gross errors are not included in the accuracy measure estimated with spectral analysis.

Figure 4.5 Selected six profiles (A, B, C, D, E, and F) for accuracy estimating with spectral analysis

Figure 4.6 Selected profiles for accuracy estimating with spectral analysis
In Figure 4.6, the X-axis of old DTM has a unit of 25 meters because of the resolution of the old DTM. Similarly, the X-axis of new DTM has a unit of 10 meters. The highest elevation of the profile in old DTM is located slightly before 120. The same DTM profile position is 300. Meanwhile, the highest elevation of the profile in new DTM is locating about at the position 320. It means there is about 200 meters horizontal shift between the two DTMs, simply judging by the position of the highest elevation. Apart from the horizontal shift, the figures of the profiles are not similar. The only reliable explanation is that the DTMs are not correctly georeferenced.

In the frequency spectrum figures, since the amplitude of the Fourier transform is symmetrical, they are only depicted in half sampling spaces, and the Y-axis is in logarithm scale to display the subtle difference. From the figure, it can be seen that the amplitudes of the spectrum transformed from the profile of the new DTM are generally less than $10^{-1}$, and those of the new DTM are generally larger than $10^{-1}$. Generally speaking, the amplitude variance related with the new DTM profile is smaller than that related with the old DTM, with one exception located at the middle of the X-axis. It can be related to the biggest elevation variance of the profile, where the elevation variance of the new profile is 244 meters, and the variance of the old DTM profile is 190 meters. Through calculating, the standard deviation of the amplitude related with the old DTM profile is 4.73, while that of the new DTM profile is 2.75. It can be interpreted that the new DTM profile includes less high frequency effects, which can be related to errors.

Table 4.2  Accuracy estimated with spectral analysis and statistics of these accuracies

<table>
<thead>
<tr>
<th>Profile</th>
<th>Old DTM</th>
<th>New DTM</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.44</td>
<td>0.45</td>
</tr>
<tr>
<td>B</td>
<td>0.48</td>
<td>0.45</td>
</tr>
<tr>
<td>C</td>
<td>0.88</td>
<td>0.51</td>
</tr>
<tr>
<td>D</td>
<td>0.46</td>
<td>0.46</td>
</tr>
<tr>
<td>E</td>
<td>0.51</td>
<td>0.49</td>
</tr>
<tr>
<td>F</td>
<td>0.43</td>
<td>0.43</td>
</tr>
<tr>
<td>Max</td>
<td>0.88</td>
<td>0.51</td>
</tr>
<tr>
<td>Min</td>
<td>0.43</td>
<td>0.43</td>
</tr>
<tr>
<td>Mean</td>
<td>0.53</td>
<td>0.47</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>0.17</td>
<td>0.03</td>
</tr>
</tbody>
</table>
Figure 4.6  The profile with the biggest accuracy estimate (C) and its Fourier frequency spectrum. The left two graphs are of the old DTM, the grid size is 25 meters; the right two graphs are of the new DTM, the grid size is 10 meters. In the upper graphs, blue line denotes the original profile, and the magenta line denotes the levelled profile.

4.5  **Accuracy estimated with checkpoints**

To discover the causes of big difference happening between the old DTM and IKONOS DTM, ten checkpoints are used to calculate the accuracy of these two DTMs. These checkpoints are spot height points on the topographic map with the scale of 1:50000, although it is known that they should be read from a larger scale topographic map. The reason is that larger scale topographic maps are not available for us. The planar coordinates of these points are measured on the scanned map, and the elevation values are read directly from the map. With these ten checkpoints, the accuracy of the old DTM is calculated as 20.12 meters, and 17.41 meters of the new DTM (Table 4.3). The maximum differences are 41.17 meters and 32.75 meters respectively. It is testified again that the new DTM has a higher accuracy than the old DTM. This result is same with that of spectral analysis.
## 4.6 Test result of the developed tools

The accuracy estimated with spectral analysis is constituted with two parts. One is the effect of the measuring error, and another is the effect of sampling and interpolation error. In this research, measuring error is set to 0.5 meters, because the generated automatic tie points have the accuracy of 0.20 pixels, and the other points will have a lower matching accuracy because of less favourable matching conditions. The effects of measuring error are the same for all the profiles; its square is equal to 0.18 meters. The interpolation method is assumed to be linear interpolation, as interpolation method does not affect the accuracy estimation greatly (Tempfli 1999). The accuracy components for the selected profiles in the new DTM are listed in Table 4.4. From this table, it can be seen that all the errors of sampling and interpolation are less than the error caused by measuring error.

<table>
<thead>
<tr>
<th>Profile</th>
<th>Square error of sampling and interpolation</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.02</td>
</tr>
<tr>
<td>B</td>
<td>0.02</td>
</tr>
<tr>
<td>C</td>
<td>0.08</td>
</tr>
<tr>
<td>D</td>
<td>0.03</td>
</tr>
<tr>
<td>E</td>
<td>0.06</td>
</tr>
<tr>
<td>F</td>
<td>0.01</td>
</tr>
<tr>
<td>Mean</td>
<td>0.04</td>
</tr>
</tbody>
</table>

To investigate whether the sampling and interpolation error is underestimated, and to test the correctness of the developed program, a test is conducted on a sinusoidal input. A whole period of sinusoidal wave is sampled with even numbers, from 4, 8… to 100, to simulate the sinusoidal wave. The purpose of sampling in even numbers is to meet the requirement of FFT. Evenly distributed 100 points on the sinusoidal wave are used as checkpoints to calculate the accuracy of the interpolated sinusoidal wave. The sampled wave value of the checkpoint position between the sampling ranges is calculated with the sinusoidal wave values at the sampling points, using linear interpolation. The calculated RMSE with this method includes only the error of sampling and interpolation.
The sampling and interpolation errors are also estimated with spectral analysis. The calculated results are plotted in Figure 4.7. The sampled waves and original waves, as well as the Fourier transform spectrums at the sampling number of 4, 10, and 100 are shown in Figure 4.8. The results state that the accuracy estimated with spectral analysis is not underestimated, and the closeness of these two accuracies is greatly affected by the selection of sampling numbers. When the sampling number is 4, from the spectrum graph it looks like there are three frequencies in this range. The similar result holds for the sampling number of 10. When the sampling number increases to 100, it can be seen that the frequency spikes are very prominent.

Figure 4.7  Error of sampling and interpolating estimated with spectral analysis and checkpoints
4.7 Analysis and discussion

One reason for the big elevation difference between the old DTM and the new DTM is the problem of coordinate systems. As mentioned before, the new DTM applies Beijing 1954 Coordinate System, and the old DTM applies Xian 1980 Coordinate system. There are coordinate shifts and rotations between these systems. Besides, the coordinate transforming parameters used here for new DTM transforming from WGS 1984 to Beijing 1954 may not be accurate, and it may bring error also. The old DTM and new DTM are not horizontally matched, thus the elevations are not of the same ground point. Its effect in plain is relatively small, as shown in Figure 4.3, but big difference will happen in the mountain area, where the elevation of peak in the old DTM may happen to be compared with the elevation values of the points other than the peak.

The same reason may lead to the big difference happening between the new DTM and checkpoints. The coordinate system applied in the 1:50000 topographic maps is Xian 1980 Coordinate System, and it is different from the coordinate system used in the new DTM. Because the spot height points are
acquired from the scanned 1:50000 topographic map, the horizontal accuracy will be lower than the accuracy of the topographic map. It will lead to the big difference between the old DTM and checkpoints. The checkpoints should come from larger scale topographic map, instead of the same scale in this case.

Since there is no accurate checkpoint that can be used, the exact elevation accuracy of the DTM generated from the IKONOS images is not tested. Due to some matching difficulty, blunder may still happen. This can be seen in the upper part of Figure 4.2, in which a region (black spot) with apparently much lower elevation appears in the river area close to a building cluster and a bridge. It proves our argument about the gross error should be removed from the new DTM before it is used as updating or upgrading reference.

The histogram of the difference between two DTMs shows a close to normal distribution. The non-zero mean tells that there is systematic error either in the old DTM or in the new DTM. The problem of adopting different coordinate systems may also result in systematic deviation in the difference of two DTMs.

The determination of measuring error is important for the accuracy estimation with spectral analysis. In this test, automatic image tie points generated by the software are used to correlate the images. Sixty-six tie points are generated for the whole image ranges with an accuracy of 0.20 pixels. Since not all the points have the same matching condition as the tie points, the measuring error will be larger than 0.20 meters. It is reasonable to set the measuring error for the spectral analysis to 0.5 meters. If we want to determine the exact figure, we can measure the same point in the stereo model for several times. It can give a more accurate estimation of the measuring error. Once this figure is determined, it can be used for the similar cases of DTM updating with IKONOS images.

It is not reliable to assume the same measuring error for the old DTM in this test. Since the additional information about the old DTM is not available, we cannot know the exact figure of the measuring error. Assuming the same measuring error enable us to compare the errors of samplings and interpolation between two DTMs. If the standards about the DTM production are available, the measuring error for the old DTM can be acquired from specifications for the measuring error in the standards.

From the accuracy figures estimated with spectral analysis (Table 4.2), it can be seen that different profile selection results in different accuracy estimates. In practice, we should select the profile with high elevation variance to estimate the accuracy with spectral analysis.

The method of accuracy estimation with spectral analysis assumes that the systematic errors and gross errors have been removed. So the accuracy figure does not include the effects of these errors. The accuracy estimated with spectral analysis is much smaller than the accuracy estimated with checkpoints. In the DTM updating practice, the systematic error and gross error should be detected and removed or reduced before using spectral analysis to estimate the accuracy and carrying out the other analyses.
The effects of buildings and vegetation are not completely filtered by the LPS software. It is one possible source of the big difference between the two DTMs. It is necessary to carry out filtering before further analyses. Several methods of filtering have reported and compared, but there is no perfect filter fitting for all kinds of terrain types. DTM point status image is useful information for the filtering, as it specifies the location of the suspicious elevation values.
5. A new filtering approach

5.1 Basic concepts

The second set of test data are aerial photographs of Moers in Germany. This is a flat rural area with elevation varying from 14.9 meters to 43.1 meters, and the elevation change mainly happens in the range of a small hill located in the eastern part. Railways are surrounding this hill and run across the whole study area. Along the railways and some roads are sparse forests. There are some building clusters, some forests, as well as some water bodies. The remaining areas are fields (Figure 5.1).

The aerial photos of this area are taken in October of 2003 with the scale of 1:3500 and pixel size of 22.5 micrometers. DSM is generated from these photos with LPS automatically at 2-meter resolution. An area of 550 rows by 1100 columns is selected. Using the available 5 checkpoints, which are generally located around the road crosses and not covered by trees, the RMSE is calculated as 0.10 meters. This accuracy is high. However, when we analyse the DSM carefully, some natural objects and man made objects can easily be discerned (Figure 5.2). Apparently, what we obtained by LPS is not a DTM yet, with the matching points located on the roofs and tree canopy (Figure 5.3, 5.4). To generate a genuine DTM with reference to the bare ground, the filtering work is necessary. On the other hand, DSM filtering only needs to remove the height of these features from the DSM. It makes the filtering task a little easier than object reconstruction.
Figure 5.2  DSM generated from the aerial photographs of the study area. The longitudinal structures along the west bottom of the hill are two trains on the railway.

Figure 5.3  3D plot of the building cluster with vegetation. The DSM resolution is 2 meters; the elevation unit is meter.
For this research, a kind of knowledge-based approach to DSM filtering has been developed. The basic idea is to take advantage of the elevation, as well as the outer shape of the objects included in the DSM, to find and delineate these objects, and then substitute or interpolate the elevation values of these points with its neighbors’ elevation under some criterion. It is necessary to mention that a slope-based concept for filtering has already been reported (Sithole and Vosselman 2004). The method used here is to form the border of an object with the elevation difference, and then try to find the outline of the object in order to determine the object type.

Big differences between DSM and DTM happen in the areas of buildings, trees, and roads. The building objects can be described as follows:

- A building is usually of rectangle shape or has parallel edges at least
- A building is build up from smooth planar surface
- A building is higher than the ground
- The size of a building has a certain range
- Buildings are often clustering

The vegetation (trees and bushes) are characterized by:

- Being higher than the ground
- Having big variation in height in its local neighborhood
- Being located around the buildings, along the road, or cluster to forest
The road objects are characterized by:

- Having a horizontal (or gradually inclined) smooth surface
- Having linearity (over longer distances than buildings) and consistency of width
- Sometimes being higher (or lower) than the ground (cut and fill)

In this research, the main concern is the DTM. Though the road extraction is not intended, we are interested in road detection because along new roads terrain change may also occur, especially in the cases of highways and railways. Another object that affects the accuracy of a DTM is the water body. Without the delineation of its border always makes the DTM look rough because of the matching difficulties and affect the ultimate quality of the DTM.

The above descriptions are for the buildings, trees, and roads. In real situations, these objects affect each other and make the elevation and shape in DSM different from a single object. For example, assuming a building has a rectangle shape and a height of six meters, in the DSM, the appropriate location may not be a rectangle outline with six meters higher above its neighbor. Contrarily, the figure may be some straight lines with one or two right angles between them, and the other sides are curved. This is the effect of the vegetation surrounding the building. The elevations of points on bare ground between buildings change gradually instead of abruptly, because of the interpolation strategy adopted in automatic image matching software.

The conceived method starts from locating protruding objects in the DSM. If the difference between a pixel and its eight neighbors is larger than the specified threshold, then this pixel is labelled. When all the pixels in this DSM have been scanned, the labelled pixels are clustered to objects. Some statistics are calculated on this cluster and its neighbor. These statistics are:

- Area of this cluster \( S \)
- Mean elevation of this cluster \( h_c \)
- Standard deviation of cluster elevation \( \sigma_c \)
- The amount of straight lines in the border of this cluster, with a minimum length constraint \( n_{SL} \)
- The amount of right angles formed by the border lines \( n_{RA} \)
- The length of this cluster \( l_{maj} \)
- The mean width of this cluster \( l_{min} \)
- The mean elevation of the close neighbor points without labels \( h_N \)
- The standard deviation of these unlabeled elevation values \( \sigma_N \)

These statistics are computed to determine the type of this cluster and the way of rectifying the elevations of this cluster.
To determine the building type, the following conditions should be met:

\[
\begin{align*}
& h_c - h_N \geq 2 \\
& 36 \leq S < 50000 \\
& \sigma_N < 0.5 \\
& n_{sl} \geq 1 \\
& n_{RA} \geq 1 \\
& \frac{l_{maj}}{l_{min}} \leq 10
\end{align*}
\]

The following conditions are used to justify a cluster is an elongated forest or not.

\[
\begin{align*}
& h_c - h_N \geq 1.5 \\
& \frac{l_{maj}}{l_{min}} > 10 \\
& \sigma_c < 0.8
\end{align*}
\]

For a forest, the qualifications are:

\[
\begin{align*}
& h_c - h_N \geq 1.5 \\
& \sigma_c < 0.8 \\
& \frac{l_{maj}}{l_{min}} \leq 10 \\
& S \geq 50000
\end{align*}
\]

The units for length and elevation thresholds are meter. The unit for area is square meter. These thresholds are acquired with inquiring different objects displayed in ArcGIS. It is necessary to mention that the threshold values are used for the flat and large scale application area. Even in this case, the specific values should be determined by test.

Once the type of the cluster has been determined, the next step is to substitute the elevation values of the cluster with the neighbor elevation values or interpolated values. In the case of a building, the elevation values of the cluster are substituted with the mean elevation value of the neighbor points, because the area of a building is relatively small and the building is often erected on horizontal ground. For the long strip forest, the elevation values of the cluster should be interpolated from the direct neighbors, considering the elevation variance of the terrain.

The condition is complex for the dense forest blocks. The assumption that the terrain of the forest area is flat is not always true. Subtracting the mean vegetation height is a direct solution to meet the low accuracy requirement. However, estimation of the vegetation height is difficult. It can be roughly estimated with subtracting the mean elevation of the cluster and the mean value of its neighbour. After the subtraction, a smoothing filter can be applied. When the forest is sparse, the whole forest area is divided into separate small clusters, and the elevation value will be substituted with the sparse
elevation values of the bare ground. In some degree, this method will produce better result comparing to the dense forest.

### 5.2 Edge forming

The edges are found by scanning the entire DSM. If the elevation difference between one pixel and its close neighbors is larger than 1.0 meter, which corresponds to the slope angle of $27^\circ$, the pixel is labelled. Through this operation, the outer shape of the protruding objects can be delineated. However, the labelled object border is not continuous. In some situations there are five blank pixels between the labelled pixels on the border. It brings a big challenge to the automatic object detection. If the search range is limited to the eight neighbor pixels, the whole border of the object cannot be extracted. When the search range is enlarged so that the border pixel of 5-pixel away can be linked together, another object is inevitably added to this cluster. When the threshold of the neighbor pixels is set to 0.6 meters, which corresponds to the slope angle of $17^\circ$, many borders are continuous (Figure 5.5). On the other hand, some close but separate objects are now linked together.

![Figure 5.5](image-url) The delineated outer shape with elevation difference threshold method. The threshold used here is 0.6 meters.

In contrast, Sobel filters are applied to the DSM to extract the edge. The applied Sobel filters are:

\[
\begin{array}{ccc}
1 & 2 & 1 \\
0 & 0 & 0 \\
-1 & -2 & -1 \\
\end{array}
\quad
\begin{array}{ccc}
-1 & 0 & 1 \\
-2 & 0 & 2 \\
-1 & 0 & 1 \\
\end{array}
\]

With many little noise values existing in the DSM image, the extracted edges are not very good (Figure 5.6, 5.7).
5.3 Border tracking method

The outer shape of the protrude object is delineate with the elevation difference threshold method. In the case that an object does not have a flat top, such as a house, not only the outer border is delineated, but the points surrounded by the outer border are also delineated. On the other hand, due to the effects of other objects and the interpolation strategy adopted in the image processing software,
the delineated outer shape may not be continuous and of one pixel wide, and may have holes. When we zoom in the Figure 5.5, we can find these situations as shown in Figure 5.8, in which the labelled pixels (red) of DSM are overlapped on the orthophoto to discern possible objects better.

![Figure 5.8 Labelled pixels (red) of DSM and orthophoto](image)

Since the situations of the labelled pixels are very complex, we need to locate the outer pixels of an object or a cluster to determine the type of this object or cluster. It cannot be finished with simply searching the eight neighbors. Apparently, a complex border tracking method is needed. The border tracking method developed in this research is described below.

The whole area is scanned by column in every row. When a non-empty pixel is encountered, it must be a border point of a cluster. This point is set as the start point of the tracking. The border tracking is carried in clockwise direction, when the end point meets the start point, the whole outer border is found. The specific algorithms are detailed as follows.

There are eight pixels around pixel (i, j), the right neighbor of (i, j) is coded with 1, and then the other neighbors are coded in clockwise direction, that is, the lower-right neighbor is coded with 2, the lower neighbor 3, and so on (Figure 5.9 left). In addition to the coding of the neighbor pixels, the entry direction should be recorded to ensure that the clockwise rule is followed. The direction from pixel (i, j) to its right neighbor is designated as 0°, the lower-right 45°, the lower 90°, until to the upper-right 315° (Figure 5.9 right). It functions like the normally used azimuth; the only difference between the entry direction and the azimuth is that the start entry direction is 90° right of the azimuth.
The entry direction is used to determine the possible candidate range for the next border pixel. The applied rule is listed in Table 5.1. The border point must have the biggest amount of empty neighbors. Though, in some cases, some non-empty candidates may have the same amount of empty neighbors. To solve this problem, small angle change rule is used to select the candidate, that is, if the candidate have the same direction with the entry, it is selected; otherwise, if the candidate direction is 45° left of the entry direction, it is selected; and then the 45° right, 90° left, and 90° right. If all the candidates are empty, then a certain amount of pixels on the right side along the entry direction are scanned in turn. If one of them is not empty, then it is the border pixel; otherwise, the tracking is terminated.

Table 5.1 The next border pixel candidates

<table>
<thead>
<tr>
<th>Entry direction</th>
<th>Code of the next border pixel candidates</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1, 2, 3, 7, 8</td>
</tr>
<tr>
<td>45</td>
<td>1, 2, 3, 4, 8</td>
</tr>
<tr>
<td>90</td>
<td>1, 2, 3, 4, 5</td>
</tr>
<tr>
<td>135</td>
<td>2, 3, 4, 5, 6</td>
</tr>
<tr>
<td>180</td>
<td>3, 4, 5, 6, 7</td>
</tr>
<tr>
<td>225</td>
<td>4, 5, 6, 7, 8</td>
</tr>
<tr>
<td>270</td>
<td>1, 5, 6, 7, 8</td>
</tr>
<tr>
<td>315</td>
<td>1, 2, 6, 7, 8</td>
</tr>
</tbody>
</table>

Up to now, the steps and criteria for border points tracking are as follows.

- Scanning the big elevation difference image in row order, for every row in column order, the first non-empty pixel is the border point, and it is saved as the start point.

- The first entry direction is designated as 0.

- According to the entry direction, decide the next border point candidates, for every non-empty candidate pixel, find the amount of empty pixels of the eight neighbors. The amount of empty pixels around the empty pixel is set to zero.

- The pixel with the highest amount of empty neighbors is selected as the next neighbor point, the according entry direction is saved for the next loop of candidate finding.

- For the case that several candidates have the same maximum amount of empty neighbors, the
small direction change from the entry direction is selected as the neighbor points. When the 
change directions are the same, say all in 45° or 90°, the left side pixel along the entry direction 
take the advantage over the right side pixel.

- When the five candidates are all empty, this is the case of a single pixels stripe, a specific amount 
of pixels on the right side of the entry direction are scanned, if one of them is not empty, then this 
pixel is selected as the border point, here it is called complement pixel; the direction to the 
complement pixel is set to the same direction from the border point to the pixel that is on the right 
side following the five candidates. For example, for the 45° entry direction, the candidates are the 
pixel of 1, 2, 3, 4, and 8, the following neighbor pixel out of the candidates range and on the right 
side of the entry direction is pixel 5, and the direction from the border point to this pixel is 180°.

- If all the pixels along the right side of a single pixel strip are empty, the border tracking is 
terminated. Or the end point meets with the start point, it is the clue that all the border points of 
this cluster have been found out; the border tracking of this cluster is finished.

- For the purpose of finding out the figure of the cluster and elevation statistics, all the border 
points of this cluster are stored, and the appropriate pixels in the big elevation difference image 
are set to zero.

- The image is scanned further to find out all the cluster borders.

With this method, the border of a complex cluster case as in Figure 5.10 can be identified. The border 
tracking process is listed in the Appendix. Although the result is encouraging, when we apply the 
rules to delineate the borders of simple clusters as shown in Figure 5.11, unwise routes or even wrong 
routes are taken.

In Figure 5.11, in the left cluster, the normal clockwise way to the second border pixel is going 
straight, while in this case it goes down. When the border tracking is around the left turn at pixel A, it 
should go to the upper left pixel (B), instead of the upper right one. In the right cluster, similar 
mistakes are made. It is stated that one basic fact of the edge has been neglected, that is, the edge 
pixels should be close to the empty pixels. Considering the situation of a pixel with the entry direction 
of 0, when its neighbor pixel 1 is not empty and pixel 2, 3 or pixel 7, 8 are empty, the next border 
pixel is pixel 1; if pixel 3 is empty and the pixel 1, 2, 7 and 8 are not empty, the border tracking 
should turn right. Combining these criteria to those stated above, the border-tracking algorithm 
performs much better.
Figure 5.10 A complex border case, gray pixels denote the cluster. Using the entry direction and maximum empty neighborhood criteria, all the border pixels are visited in turn. Detained explanation is noted in Appendix.

Figure 5.11 Wrong border-tracking examples. Gray pixels denote the cluster. In the left cluster one border pixel (B) is left out; in the right cluster, two border pixels (C and D) are missed. Arrow denotes the entry direction of the pixel.
5.4 Results

The original aim of the border tracking is to delineate the outer range of the cluster and to test whether the border pixels can form direct line and some right angles, which would be a cue for buildings. With the above border-tracking algorithm, the extracted border is one pixel wide and matches with the cluster well (Figure 5.12, 5.13, 5.14). Due to the complex situations, for example, the cluster with holes and two clusters are linked with only one pixel, automatically tracking the border of the cluster is challenging. In some cases the endpoint does not meet the start point, thus open polygons are produced. In this research, the open polygon is closed with straight line in order to remove the effects of buildings and vegetation.

It is believed that realisation of automatic testing the amount of straight lines and right angles could not be accomplished in short time, so this work is not carried out in this research. The cluster type of building or forest is not differentiated. Instead, the elevation rectification method is determined by the parameters of area, mean elevation of the cluster, mean elevation of its neighbors, standard deviation of these neighbor elevation values, and the ratio of length to width. If the area of a cluster is less than the maximum threshold for the building and the standard deviation of the neighbors’ elevation is less than 0.25 meter, the elevation values of this cluster is substituted with the mean neighbor elevation value. Otherwise, the elevation values of this cluster are interpolated from the neighbor elevation values. For an elongated cluster, if the ration of its length to width is larger than 10, the elevations of this cluster are interpolated also.

Figure 5.15 is the filtered DSM. It looks better than the old one, as the effects of buildings and forests have been removed or reduced. After filtering, the same building cluster as shown in Figure 5.3 is depicted in Figure 5.16. Using the same five check points, the RMSE is calculated as 0.10 meters. It is not surprising, because the checkpoints used are distributed on the uncovered open ground and these areas are not rectified. The difference between the unfiltered DSM and filtered DSM is shown in Figure 5.17. Among 550×1100 pixels, 89812 pixels are rectified; the ratio of rectification is 14.8 percent.

Excluding the pixel with value 0, which means no rectification, the mean elevation rectification is 2.6 meters, with a standard deviation of 2.4 meters. The minimum rectification value is 0.1 meters, and the maximum rectification value is 21.3 metres. Through checking the aerial photos, the maximum difference is found to be a blunder produced in the DSM generation.
Figure 5.12  Extracted border

Figure 5.13  The extracted border (red line) and the objects in orthotphoto. The extracted borders match the outer range of the building clusters well.
Figure 5.14  The location of extracted border, comparing with the orthophoto and DSM. Left: extracted border and the orthophoto. Right: extracted border and the DSM. Red pixel denotes the extracted border.

Figure 5.15  The filtered DSM
Figure 5.16 3D plot of the filtered building cluster as shown in Figure 5.3. The DSM resolution is 2 meters; the elevation unit is meter.

Figure 5.17 The difference between unfiltered DSM and filtered DSM
5.5 Discussion

The developed filter method can be used to remove the effects of the buildings and vegetations. Though the information about the straight lines and right angles formed by border pixels is not used, the building clusters and forests are still delineated and rectified, based on the knowledge about these objects and the study area. The whole process is fully automated, except for finding threshold, and can be completed in sixty minutes. For the flat area and large scale application cases, it is believed to be valid and effective. It is likely to work also in undulated and even in rough terrain, if the threshold is large and pixel size is small.

The elevation difference threshold used here is 0.6 meters, if an object is 0.6 meter higher than its neighbors, it will be delineated and rectified. If the difference between the noise value existing in the DSM and its neighbor is larger than the threshold, it can be removed also. However, to some extent, the effects of the buildings and vegetations may still be included because the tracked border is open polygon and the threshold is big. The interpolation method used here is inverse distance weight; it makes the interpolated region a little unnatural (Figure 5.16).

The elongated forest has been removed, as well as the railway covered by the forest. Eliminating the elongated forest is anticipated, but for the case of railway covered by forest, as in this study area, or the case of canal covered by forest, rectifying the elevations of the cluster with the elevations of neighbor points is not intelligent, because the railway is generally higher than its close neighbors, and the canal is lower than the banks. From the aerial photograph shown in Figure 5.1, the railway can be seen, but you cannot find some lower elevation value in the corresponding position of the DSM generated from this photograph (Figure 5.2, 5.4). This is a defect of the automatic image matching method. The geometric figure of the elongated forest, such as the curvature, can help to determine whether it is pure forest or forest covering railway or canal. This is the future research question. At the present, acquiring the correct elevation value of the railway has to rely on human checking.

The elevation difference threshold for edge forming is one of the key factors for this filter method. If the threshold is too big, the edge will not be continuous, and thus puts big burden on edge tracking. If the threshold is too small, the neighboring clusters will be linked together, and the elevation values of the points in between will not be used for correction. It will bring some errors to the new elevation. The elevation difference threshold can be determined with the terrain slope and the DSM grid size. In order to resolve the problem of holes and gaps between edges, the cluster can be filled if the elevation values in this cluster are larger than the threshold and they vary in a certain range. It is a kind of segment technique. An iterative procedure will also help in selecting a good threshold and also removing the lower protruding object.

Border tracking is another key factor. Generally the border is found with the derivative information of the intensity. The Canny method finds edges by looking for local maxima of the gradient and use two thresholds to detect strong and weak edges. It is said that Canny method is less affected by the noise and more likely to detect the true weak edges. There is a program for edge detection in the Matlab
toolbox of image and video processing. However, this toolbox is not available here. It is also argued that the Canny and Sobel methods work fine for gray value images but not so well for range images, such as DSM. Due to the limitations of resource and time, this edge detection method is not applied and not compared with the method used here.

Automatic detecting the break lines is a challenging task. In the lake area, the DSM looks like a polyhedral surface generated by a TIN (Triangular Irregular Network) (Figure 5.2). There are two low points in the left lake and possible reason for which is that some objects were on the lake when the aerial photograph was taken. For the top right lake, the nodes of the electric power lines cause the prominently high points in the lake area. In the DTM generation processing of LPS, specific areas can be manually delineated. This will reduce the difficulty of DSM filtering. In this research, the lake border was digitized on the orthophoto and the appropriate points in the lake area were specified with a unique elevation value. It makes the lake look better. However, the irregular figure of this area may help detect the water body automatically.
6. Tests on the filtered DSM

In order to test whether the accuracy measures are sufficient for detecting change and poor filtering, and whether the discriminant for change and poor filtering work or not, we have some tests on the unfiltered and filtered DSM of the Moers area. In these tests, we assume the filtered DSM as the old DTM, the DSM as new DTM, and the gross error and systematic error have been eliminated.

6.1 Accuracy estimated with spectral analysis

When applying the spectral analysis to estimate the accuracy of the filtered DSM and the original DSM, we assume they have the same measuring error. It is reasonable because only filtering processing is done on the original DSM. In order to get accurate estimates, a profile passing across the small hill is selected to estimate the accuracy of the unfiltered and filtered. The selected profile is shown in Figure 6.1.

![Filtered and unfiltered profile](image)

Figure 6.1 Selected profile to estimate the accuracy of the unfiltered and filtered DSM. The resolution of the DSM is 2 meters. The unit of the elevation is meter.
Since the aerial photographs were taken with a normal angle camera, we assume the measuring error is 0.2 meters. The variance of the unfiltered profile and filtered profiles can be estimated with Equation (3.10). For the unfiltered profile, the estimated variance is 0.0310 meters. The variance of the filtered profile is estimated to be 0.0297 meters. Thus the standard deviation of the difference $\tilde{\sigma}_d$ can be estimated with Equation (3.18) as 0.25 meters.

### 6.2 Statistics of the difference

The standard deviation of the difference can be calculated with Equation (3.16) as 1.3 meters. The statistics of the difference between these two DTMs are listed in Table 6.1.

<table>
<thead>
<tr>
<th></th>
<th>Statistics of the difference between the unfiltered DSM and filtered DSM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min</td>
<td>0</td>
</tr>
<tr>
<td>Max</td>
<td>21.3</td>
</tr>
<tr>
<td>Mean</td>
<td>0.4</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>1.3</td>
</tr>
</tbody>
</table>

### 6.3 Analysis of the difference

The difference is shown in Figure 5.17. We can find both of the following conditions are met. According to our criteria, it means that there is change or poor filtering existing in the new DTM.

$$\sigma_d > \tilde{\sigma}_d$$

$$d_{ij} > 3\tilde{\sigma}_d$$

Since the minimum difference is 0 meter, it states that only “filling pattern” exists. Thus we can expel the possibility of terrain change. The mean difference of the whole region is positive, 0.4 meter, thus we can readily conclude that the poor filtering of the new DTM produce the big difference. To support this finding we could also rely on ancillary information: slope analysis excludes terrain change because of landslide and analysis of road buffer excludes a terrain relief change because of the absence of a pattern of cutting and filling.
6.4 Analysis of the amplitude spectrum

From the amplitude spectrum of these two profiles (Figure 6.2), it can be seen that the amplitude related with the filtered profile is less than that of the unfiltered profile and has a smaller variance.

![Figure 6.2](image) The amplitude spectrum of the unfiltered and filtered profile. Y-axis is in logarithm scale.

In order to find the filtering effects in the frequency domain, the above amplitudes are differenced and the result is shown in Figure 6.3. It states that the filtering affects the low frequency part. From the literature (Marmol and Jachimski 2004), we know that the filtering will remove the effects of the high frequency components, which are related with field objects. From this figure, it seems that the low frequency components that are assumed as terrain relief are reduced. It is not easy to interpret the difference as filtering in this test area affects various frequency components related to individual trees, various buildings, and clusters of both of different size.

![Figure 6.3](image) Difference between the amplitudes of the unfiltered and filtered profile. Y-axis is in normal scale.
6.5 Discussion

This is a simple test designed to verify whether the accuracy measures suggested are sufficient for detection of change and/or poor filtering, and to testify the correctness of the discriminant for change and poor filtering. The results show that the proposed measures are sufficient in the investigated case for discriminating change and error and to detect poor filtering.

From this result, we can expect that the discriminant can detect poor filtering in IKONOS case with the situation of 0.5 metres measuring error, 1 meter spacing, and the scene dependent differences.
7. Conclusions and recommendations

7.1 Conclusions

A knowledge-based filtering approach is developed and partly implemented for the case of high resolution DSM of a flat area. This approach takes advantage the elevation difference between the neighbor pixels in the DSM to form the edges of the objects, and then track the edge pixels to reconstruct the borders of the cluster. The type of the cluster is determined with the parameters of area, straight line number, right angle number, and the statistics of the elevation of the cluster and its neighbors. The substitution or interpolation method is applied to rectify the elevation values according to the cluster type. Due to time limitation, the determination of the cluster type is not carried out. Instead, the elevation rectification method is determined with the parameters of cluster area, the statistics of the neighbors’ elevation values. To delineate the outer borders of a cluster, an efficient border tracking algorithm is also designed in this research.

Automatic image matching can acquire high accuracy elevation values in open terrain with good texture. In this research, the automatically generated DSM from aerial photographs at the scale of 1:3500 and pixel size of 22.5 micrometers reached the accuracy level of 0.1 meters in elevation. Similarly, a DTM is generated from IKONOS stereo pair with automatic image matching. Because there are neither coordinate transformation parameters nor control points at hand, the generated DTM is referenced to a different coordinate system from an existing DTM of the same area. Big elevation differences of more than 120 meters exist between these two DTMs after roughly horizontal matching. The maximum difference is much bigger than the expected values deduced from the specifications. Through visual analysis, it is found that the big differences are not in small amount that can be attributed to blunders. It is also found that in the hill area a region of positive difference is next to a region of negative difference, and the segments of these regions do not look like landslide or cut and fill along a highway. It is believed that the big difference is attributed to the coordinate reference system.

The DTM accuracy measures of the influence of sampling and interpolation, and the influence of the measuring error, can be estimated with spectral analysis method. They can be acquired without having to rely on external reference data. This method is used to estimate the accuracy of the DTM generated from IKONOS images and the existing DTM, and the accuracy of the new DTM is higher than the old DTM. The result is the same with that of checkpoints method, even though the problem of coordinate reference system exists. The spectral analysis method for accuracy estimation is also testified with a sinusoidal wave.
In order to determine whether there is a big difference happening in specific area, some other accuracy measures are needed. The suggested measures are variances estimated and calculated from the difference between two DTMs, mean difference, and maximum difference threshold. If the calculated variance is larger than the estimated one, or the difference is larger than the maximum difference threshold, we deem that there exist significant errors, terrain changes, or poor filtering.

The pattern of cutting and filling, as well as the suggested measures, are used to analyze whether the big difference is the reason of a change or a poor filtering in new DTM. It is proved that the measures are sufficient for discriminating changes and errors and to detect poor filtering with the unfiltered and filtered DSM. Due to the unavailability of test data, it is not tested for the terrain relief change. The concept for a procedure of automatic quality control for the purpose of delineating the error prone area and the change prone area has developed. It is not tested also because of the unavailability of the test data.

Based on these concepts, a global workflow for DTM updating with high resolution satellite images is proposed. Due to the limitations of time and available test data, the effectiveness of the proposed workflow is not tested.

It is stated in the literature that only DSM can be generated with automatic image matching from the satellite images. The automatically generated DSM is needed to filter in order to get a DTM. The aerial photograph case in this research testifies the above statements. The information about the matching accuracy can be used to determine the measuring error for spectral analysis. In order to improve the accuracy of image orientation and elevation values, it is necessary to adopt GCPs to reduce the systematic error and blunders.

It is stated in the literature that automatic image matching yield best results in flat, open, and well-textured terrain, and the accuracies become bad in the areas of little texture and steep slope. According to the literature, the landslides are likely to happen in the steep slope. It is believed that there is a pattern of cutting and filling on the terrain along the road buffer, especially for the highway and railway. In order to update or upgrade an existing DTM, special attention should be paid to these critical regions of urban, forest, steep slope, and roads because of possible low accuracy, filtering necessity, and terrain changes. The steep slope can be delineated from the existing DTM. The region of urban area, forest area, and road can be extracted from the satellite images. The latter was not the subject of the presented research.

In order to compare the elevation accuracy of the new DTM and the old DTM, they must adopt the same coordinate reference system. The information of coordinate reference system adopted in the old DTM should be available. In the case that they are not in the same reference system, coordinate transformation parameters or at least four control points are necessary.

It is proved that the knowledge based filtering method developed in this research can be used to filter a high resolution DSM of a flat area. The developed border tracking algorithm can track some complex borders. The acquired filtering result is good with the building objects and forest blocks, but poor in the elongate road covered with vegetation, which actually is the defect of automatic image
matching. It is likely to work also in undulated and even in rough terrain, if the threshold is large and pixel size is small.

### 7.2 Recommendations

The effectiveness of the method suggested in the literature for detecting and reducing systematic errors and gross errors contained in the DTM should be tested. If the existing method does not work well, a new method should be developed.

This research suggests that the terrain change in steep slope and road buffer can be detected with the pattern of cutting and filling. Because there is no appropriate data, this concept is not testified. The application of the spectrum analysis on determining the effects of filtering needs to be investigated.

Although the accuracy measures suggested in this research are testified to be suitable to detect poor filtering, the measures that are useful in explaining the difference between two DTMs of the same area is not identified. It needs to be explored in the future research.

It is believed that wavelet transform can be used to analyze the difference between two DTMs. Because the related test data are not available, this method is not applied in this research. It is an interesting topic to investigate its effectiveness in local analysis and compare the method suggested here.

For the filtering approach, the forming of straight line and right angle needs to be investigated. They are necessary for determining the type of the cluster, which will improve the effects of the filtering. For a rough terrain case, an efficient filtering method should be selected or developed in order to update the DTM automatically.
Reference


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symposium on spatial data quality 2003, Hong Kong.
The border tracking process of the cluster in Figure 5.10

<table>
<thead>
<tr>
<th>Entry direction</th>
<th>Border pixel</th>
<th>Candidate pixels</th>
<th>Empty pixel amount around candidates</th>
<th>Complement pixel</th>
</tr>
</thead>
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<td>0, 6, 0, 0</td>
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</tr>
<tr>
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</tr>
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</tr>
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<tr>
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### Glossary

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<tr>
<th>Abbreviation</th>
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<tbody>
<tr>
<td>CE90</td>
<td>Circular Error at 90 percent confidence</td>
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<tr>
<td>DEM</td>
<td>Digital Elevation Model</td>
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<td>DPS</td>
<td>Digital Photogrammetric system</td>
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<td>Digital Surface Model</td>
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<td>DTM</td>
<td>Digital Terrain Model</td>
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<td>FFT</td>
<td>Fast Fourier Transform</td>
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<td>FWM</td>
<td>Failure Warning Model</td>
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<td>GCP</td>
<td>Ground control point</td>
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<td>InSAR</td>
<td>Interferometric Synthetic Aperture Radar</td>
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<td>IOR</td>
<td>Iterative Orthophoto Refinements</td>
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<td>LE90</td>
<td>Linear Error at 90 percent confidence</td>
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<td>LIDAR</td>
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<td>LPS</td>
<td>Leica Photogrammetry Suit</td>
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<td>NDVI</td>
<td>Normalized Difference Vegetation Index</td>
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<td>PCA</td>
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<td>RMSE</td>
<td>Root Mean Square Error</td>
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<td>RPC</td>
<td>Rational Polynomial Coefficient</td>
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<td>TIN</td>
<td>Triangular Irregular Network</td>
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<td>WGS</td>
<td>World Geodetic System</td>
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