Tracking Uncertainty in Derived Height Data

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Abstract This chapter discusses the tracking of uncertainty in height data derived from stereo imagery that has been obtained from an airborne electro-optical digital multi-spectral imaging system. The overall objective of the software described has been to prepare the data for input into Geographic Information Systems, and to provide the ground coordinates of the data with the greatest accuracy possible. This article has two objectives: to provide a brief overview of the digital imagery procedures used to process the raw imagery and ancillary inertial navigation system data to achieve photogrammetric adjustment, geometric correction, and terrain height extraction, and, second, to illustrate the results of processing a representative data set. One of the final products produced by the software processing systems is a mosaic of ortho-imagery, using the nadir views and the terrain height data generated from the stereo imagery.

The chapter discusses the methods and the procedures that are being developed at the Canada Centre for Remote Sensing for tracking or carrying the absolute and relative accuracies of the derived data products from the raw data through to the final products. The paper concludes with an example of some processed imagery and derived height data along with the confidence measure or uncertainty of the derived height.

Introduction

This chapter discusses the problem of dealing with uncertainty in height models, in the context of the extraction of terrain height data from stereo imagery obtained from an airborne electro-optical digital line imaging system. The primary purpose of the processing software has been to perform the geometric correction of digital multispectral data for input into Geographic Information Systems (GIS) for Remote Sensing analysis, cartographic applications, and other interpretative tasks. The requirement for preparing the imagery for input to GIS brings with it a need to specify the positional accuracy of the corrected imagery, as well as the quality, or accuracy, of any derived data products. Uncertainties or errors in the height data derived from stereo imagery can have an important effect on the uses of both the derived DEM data and orthoimages created from it. Orthoimages are created by re-projecting the original imagery and removing the distortions caused by terrain height variations; thus, any errors in the terrain height data will cause displacement errors in the final orthoimage product. The Digital Elevation Model (DEM) extraction process described in this chapter produces height data on a regular grid with a resolution specified by the user. The grid resolution of the height data can be as fine as that of the original imagery, if desired. One of the by-products of the process is a confidence measure data set, at the same resolution as the height data.

The system can achieve a high degree of accuracy. The results of a photogrammetric calibration of the system, based on a data set acquired over a photogrammetric test range, have shown that the Root Mean Squared (rms) horizontal (x and y) components of the residual errors in the 'fit to control' points are one-half of the size of the input pixels, and the vertical (z) component is one pixel. It is worthwhile to try to carry some indication of this accuracy through the various stages of data processing to the final products. The reason is that the final products will normally be comprised of data from several different flight lines, and there may be areas where the data will be interpolated or estimated. This aspect must be indicated to the user. The objectives of the processing algorithms developed at the Canada Centre for Remote Sensing (CCRS) have been to remove the motion-induced distortions from the imagery, establish the correct ground relationship of the data, and use the corrected imagery for the derivation of additional information such as terrain height.

The software described in this chapter was originally developed for an imaging instrument known as MEIS (Multi-detector Electro-optical Imaging Scanner). It contains six nadir bands and two stereo bands that look forward and aft, respectively, to provide for single-pass stereo coverage. It should be noted that the MEIS, which acquires imagery continuously across a swath during

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flight, differs from a frame camera, which acquires square frames of imagery at regular intervals.

This chapter has two purposes:

- to outline the software processing system developed at CCRS for the photogrammetric adjustment and automated extraction of terrain height from the digital airborne imagery obtained from the MEIS, and
- to show how the inherent accuracy achieved by the photogrammetric adjustment and geometric correction processes may be carried through the processing steps to the final terrain height data and ortho-image products.

Although the software was originally written for the MEIS imager, it is currently being modified so that it may be applied to a variety of other sensors such as frame cameras and satellite optical sensors.

BACKGROUND

The MEIS imager, which was developed for CCRS by MacDonald, Dettwiler and Associates of Vancouver, has been described in detail in several papers published during the last ten years (McColl, Neville and Till 1983; Neville et al. 1990; Till, McColl and Neville 1983; Till et al. 1986; Till 1987). The MEIS contains eight separate optical channels with 1024 pixels covering a field of view of 40 degrees, which provides a pixel resolution (ifov) of 0.7 milliradians (0.04 degrees). Each optical channel consists of a detector array, a lens, and a spectral filter and associated digitizing and control electronics. The visible and near infrared spectrum from 330 nm to 1100 nm is covered through the use of individual highly accurate, very narrow spectral filters. The forward- and aft-looking channels were implemented by adding external mirrors to two of the nadir channels to provide for single-pass stereo coverage (Gibson et al. 1983). The MEIS has been in operational use for over ten years and has been flown on well over two hundred remote sensing missions (Till et al. 1986). At the present time, it is under lease to a commercial operator, Aquarius Flight Inc. of Markham, Ontario. Design details and the initial flight trial results of a new imaging system called WHiRL, which is a single optical channel prototype replacement for the MEIS, have been reported by Neville et al. (1992).

AIRBORNE SYSTEM DESCRIPTION

The essential hardware components of th,e airborne package are

- the MEIS imager with its associated high density data tape instrumentation recording system
- an Inertial Navigation System (INS), and
- a general aircraft data logging system (Gibson et al. 1983).

The INS is required to measure the aircraft velocity and roll, pitch, and heading parameters, which are used in the subsequent stages of adjustment and geometric-correction processing. In addition, the aircraft's height above sea level is recorded from a high-resolution barometric altimeter. Although the Global Positioning System (GPS) was not operational when this system was developed, a GPS receiver has been added to the system for some of the later flight trials and has proved very useful.

GEOMETRIC CORRECTION PROCESSING

The basic concept behind the geometric correction and re-sampling processing is the computation of the exact location of each input pixel in the output coordinate system, followed by a re-sampling of the imagery onto a uniform grid. Two modes of processing are possible. The first, which does not take into account variations in terrain height, is used when creating stereo pairs of the forward- and aft-looking imagery that may be used for stereo viewing and also for DEM extraction. The second mode, which does correct the distortions in the imagery caused by variations in terrain height, using a derived DEM, is used to create mosaics of nadir views for multiple overlapping flight lines. Before this geometric correction processing may be attempted, it is necessary to have an accurate set of measurements of the sensor position and attitude, sampled at the same time as the image scan lines. This is accomplished by identifying control points in the imagery for which the ground coordinates are known, and then adjusting the navigation system data to achieve a minimum mean-squared error fit of the imagery to the control points. The details of this process and the resulting accuracy of the adjustment are covered in detail in the paper "Photogrammetric Calibration of a Digital Electro-optical Stereo Imaging System" (Gibson 1994). A brief summary follows.

PHOTOGRAMMETRIC ADJUSTMENT

The inertial navigation system data are adjusted to make the imagery fit the ground control points, using photogrammetric principles based on the standard Collinearity and Coplanarity conditions (Slama 1980). The Collinearity condition is applied to ground control-point measurements, and the Coplanarity condition is applied to tie multiple flight lines together, using features visible in overlapping flight lines, but of unknown location. This approach is well known for conventional photo-mapping projects. The traditional photogrammetric algorithm was modified to handle the MEIS imagery, which, unlike an aerial photograph or a frame camera, does not have a central perspective point. One of the implications of that is that the concept of the epipolar plane, familiar to users of aerial photography, does not apply to the MEIS imagery. That is because the aircraft changes attitude as successive stereo views are acquired.

A further modification was required to accommodate the time-sampled position and attitude measurement data from the INS. The position-offset and drift errors inherent in the INS data are deterministic in nature, and change very slowly with time. Thus, they may be represented in the system error model as low-order polynomials of time. The typical velocity error is less than 1 m/sec. That means that, after several hours of flying, the absolute position errors can be of the order of several kilometres. The adjustment process involves solving for the polynomial coefficients that best approximate the INS errors, and then using those coefficients to model the errors so that they may be effectively removed from the INS data.

The two condition equations contain non-linear terms involving the roll, pitch, and heading angles; thus it is necessary to derive a linear approximation to the condition equations and then employ an iterative procedure to solve for the error terms. In each step of the process, the estimated errors are removed from the data. A minimum mean-squared error solution is achieved when no further reduction of the error measure is possible.

To verify the accuracy of the adjustment processing, a test data set was acquired over a photogrammetric test range near Sudbury, Ontario. The range covers an area approximately 3 km by 6 km, and contains over 400 targeted control points. The control point coordinates have been established to 'an accuracy of 2 cm in a first-order survey network.

The data set used for the photogrammetric analysis consisted of five parallel principal flight lines, with three additional cross flight lines acquired at the Sudbury photogrammetric test site in 1992. The flying height, approximately 700 m above ground, provided a ground pixel resolution of 0.5 m. The side-to-side overlap between flight lines varied from 30% to 50%. Each flight line covered an area approximately 500 m wide and 5000 m long.

One hundred and seventy-four control-point targets were identified and measured in the eight flight lines. Two trials of the adjustment processing were conducted. In the first trial, all control points measured in each flight line were used for control; in the second trial, only five of the control points were used for control, the remaining 169 points being designated as check points. Check points are control points whose weights have been set to zero. They may be used to obtain an independent evaluation of the accuracy of the adjustment. Although the errors at each point are calculated, the zero weighting effectively prevents the measurements from contributing to the solution.

The results of the two trials are contained in Table 1, where it may be seen that the horizontal position errors for the check points are approximately one half of the pixel resolution (rms), and the errors in the vertical are approximately at the pixel resolution (rms). Note that Table I shows the differences, or errors, between the true coordinates and the computed coordinates of both the ground control points and the check points.

	Conditions	Errors: m rms		
		x	y	z
Trial 1	Control points (174)	0.20	0.20	0.39
Trial 2	Control points (5)	0.21	0.14	0.19
	Check points (169)	0.28	0.31	0.54

Table 1: Errors in Computed Coordinates (0.5 m pixel size)

Height Derivation Process

This section is a brief extract of part of a paper by Gibson, Buchheit and Hak (1994) titled "Geometric correction and terrain height extraction using stereo electro-optical digital imager." The automated height-extraction algorithm chosen for the airborne digital imagery is based on a hierarchical approach, where the terrain height data are refined in a series of processing steps until the desired resolution, or level of detail, has been achieved. The relative displacement, or parallax measurements, between two stereo views is made by a correlation process based on the method described in the paper "The phase correlation image alignment method" by Kuglin and Hines (1975). The parallax measurements are made by correlating square or rectangular patches of stereo image pairs. The image patches are selected from the respective images based on the ground coordinates of each image, and are organized to produce measurements on a regular grid throughout the region of overlap of the stereo pair.

DERIVATION OF TERRAIN ELEVATION

The imagery is initially block-averaged to reduce the amount of parallax so that the relative shift between two patches of imagery would not exceed one half of the size of the correlation patches, which are typically 16 lines by 16 pixels. Experience on a limited set of test flights has shown that a block-averaging factor of 16 lines by 16 pixels is sufficient for the initial pass. That is, for 0.5 m full-resolution imagery, the initial block-averaged imagery will have a resolution of 8 m. As the process proceeds and the terrain height data acquire more detail, the amount of block averaging is reduced by a factor of two in each dimension at each stage, until the desired resolution of the height data has been reached. The algorithm is described as follows:

1. The initial block-averaging factors are selected, based on the estimated dynamic range of the terrain height, so that the maximum parallax shift between the fore and aft views will be less than one-half of the correlation patches.
2. The block-averaged stereo images are re-sampled using the available terrain height data. For the initial re-sampling pass, a constant terrain height, usually the expected average value for the area, is selected to minimize the parallax shift in the stereo imagery.
3. The relative shifts between instances of stereo imagery are measured by the correlation algorithm for each block-averaged line and pixel location.

4. A statistical analysis is performed on the results of the shift measurements. Any points that are statistical outliers within a local region are replaced with a value interpolated from the surrounding valid points.
5. The processed shift values are then converted into height values and added to the existing height data.
6. The height data set is then interpolated to the next finer level of block averaging. The typical resolution increment is a factor of two in both directions.

As well as providing the displacement measurement, the correlation process also provides a relative quality estimate that plays an important factor in the statistical processing stages and in tracking the accuracy of the derived height data. The quality measurement can have any value between 0 (no match) and 1 (a perfect match). In practice, it has been found that processing two dissimilar images will result in a quality value of approximately 0.15.

PROCESSING DIFFICULTIES

Not unexpectedly, there are several aspects to the processing that pose varying levels of difficulty, which must in some cases be solved by manual intervention. The net result is that some parts of the terrain height data set will be interpolated or inferred from nearby valid points, and therefore must be flagged as having lower accuracy than the remainder of the data. For this reason, each element of the derived-height data set consists of a pair of values:

- the height, and
- a relative weight value set based on the estimated accuracy of the computations involved in establishing the height value.

Any data values created by the processes described below will be assigned proportionally low weights.

1. *Edge and End Effects* Because of the finite size of the correlation patches, it is not possible for the derived height data to extend to the full length and width of the imagery data. This is further complicated by the irregular nature of the aircraft trajectory, which can cause portions of the forward and aft imagery to have less than 100% overlap.

   On edge flight lines that do not overlap on one side with another line, the effect of the reduced coverage of the height data is that the intermediate passes of resampled imagery may be badly sheared at that side when there is a substantial amount of terrain relief. When two flight lines overlap, this problem is largely solved by the statistical processing because the edge of one flight line falls on the interior of the neighbouring one. The questionable edge measurements that will have low quality or weighting values can be easily weeded out by the statistical processing. The problem of estimating the height outside the outer boundary of the entire area has been handled by gradually blending the last valid height values with the average datum level in a band outside the border. Fortunately, since the resolution is increased in each iteration step, the boundaries of the valid height data are enlarged so that, in some cases, a value that has been estimated at one processing stage may be replaced by a good measurement at the next stage, and the weight of the point will be increased to reflect its improved accuracy.
2. *Water Bodies* Bodies of any significant size in the imagery can cause erroneous shift measurements. This is largely the result of sun-glint effects in the imagery; different views of a water body can sometimes contain dramatic differences in the reflected intensity from the water surface. This in turn can result in wild variations in the measured shift values from the correlation processing. This is a case where manual intervention is required. An operator running a height editing program simply defines a polygon which follows the boundary of the water body and then replaces the height values in the interior of the polygon with the average value of its boundary. The weights for all points in the polygon will be assigned low values.
3. *Occlusions* This is the most difficult and sometimes intractable problem that can occur. It arises when the slope of the terrain exceeds the off-nadir angle of the fore/aft imagery, and simply causes gaps in the coverage of one or another of the stereo views. Generally, the solution to the problem will require some judicious manual editing of those areas that are not cleared up by the statistical processing. Fortunately, in the cases handled so far by this processing system, the number of occlusion areas has been very small, and thus easily handled by the manual editing process.

Tracking Uncertainty in Derived Height Data

The relative weight value, or uncertainty, of each calculated or estimated point in the derived height data may be used to track the accuracy of that point throughout the height derivation process by ensuring that the weight is updated at each processing stage. When the height-extraction process has been completed, the relative weights may be converted to an absolute measure by incorporating information obtained from the intersection computations for specific points measured in the stereo pairs of imagery. The adjustment algorithm produces a report showing the errors in the control points and the check points, as well as an estimate of the errors to be expected in computing the coordinates of any selected feature. The weight values in the height data may be scaled to correspond to the expected errors, based on the adjustment report. While this procedure does not produce an exact calculation of uncertainty throughout the data set, it will nevertheless provide the best estimate available under the circumstances. During the processing, any heights whose weight values are below a given threshold may be set to an arbitrary datum level and marked as invalid. The purpose is to allow for having a reasonable value for each point, so that the maximum amount of detail will be preserved in visual display products. Finally, to reduce the size of the data files, a representative error estimate may be defined for the whole data set, and an output file generated that contains only the height values, with any questionable values being replaced with zeros, or some other improbable value.

SAMPLE DATA PROCESSING RESULTS

Figure 1 contains some sample images and derived height data from a test flight performed by Aquarius Flight near Guelph, Ontario in December, 1994. The flying height for the test, approximately 1500 m above ground, resulted in 1 m resolution imagery. A subset of the test data was selected to illustrate the geometric correction and height extraction processing, as well as the capability of the system to track the uncertainty of the derived height. The test flight was conducted using a Global Positioning System (GPS) receiver in the aircraft, as well as a base-station receiver. Post-flight processing of the GPS data was carried out by Applied Analytics Corporation of Markham, Ontario. The residual errors from the GPS processing indicate sub-metre errors in the position data. Since the primary purpose of the flight was to verify the operation of the equipment, there has so far been no further verification of the positional accuracy.

The left-hand strip of imagery in Figure 1 is a composite of the nadir bands of two partially overlapping flight lines; the irregular white patch within the imagery occurred when the aircraft was blown off-course by strong winds and failed to maintain complete overlap. The centre strip is an image of the derived height data for the area corresponding to the nadir mosaic; the dynamic range of the height in the image is approximately 120 metres.

The right hand strip is an image of the relative weight values associated with the height data of the centre strip. In this image, black represents low weight; white represents high weight. The black areas in the central portion of the strip correspond to the non-overlapping region of the left-hand image. It should be noted that the derived height for each flight line is slightly wider than the nadir views. This is a result of the fact that the mirrors used to create the forward-and aft-looking bands cause them to cover a wider swath on the ground than the nadir views. The range of relative weights for the height data for this test area is approximately 0.8 to 1.0, except for the border and non-overlap regions, where it is zero. If the data were simply scaled to create a grey-scale image, it would result in a bright but low-contrast image. Thus, to emphasize the relative contrast, the weight values were clipped to a minimum of 0.7, and then mapped to the full grey-scale range.

The variations of the weight intensity represent different levels of confidence in the derived height data. It may easily be seen that the shapes of the variation patterns are very highly correlated with the features in the nadir mosaic. The weights are higher in flat areas, such as fields and streets, and lower in wooded areas and field boundaries. The information content of the weight field could thus be very useful for applications such as texture mapping, as well as in terrain-height extraction processing, where it may be used as a local roughness indicator for the statistical smoothing stage.

The DEM extraction process has also been applied to the imagery from the Sudbury test flights, with a resulting accuracy of the DEM at the control points of 1.2 m (rms). The Guelph data set was selected for the illustration in this paper because of the striking resemblance of the grey-scale weight image to the features in the corrected imagery.

Conclusion

It has been demonstrated that sub-pixel (rms) horizontal accuracy and pixel level (rms) vertical accuracy may be achieved from airborne digital imagery when rigorous photogrammetric adjustment techniques are employed. The ground coordinates of corrected nadir mosaics and terrain height data may be computed with the assurance that the position and height errors will have verifiable tolerances, and airborne digital imagery can begin to make a contribution to projects where the error tolerances are commensurate with the pixel resolution. The level of de- tail that may be provided by the dense coverage of the derived terrain-height data will allow the rapid development of accurate terrain models for many applications.

It has been found that the uncertainty, or relative accuracy (weight), of the derived height data may easily be tracked during the processing steps, and it has been shown to provide useful and consistent information relating to the quality of the terrain-height data. It is not difficult to imagine that the uncertainty data could constitute an independent output product.

The tracking of the uncertainty of the DEM data is a relatively new component of DEM extraction processing at CCRS, and it can be expected to have an influence on the processing methodology, in that modifications being made to the algorithm will provide a more reliable intersection-error measure for each element of the derived DEM.

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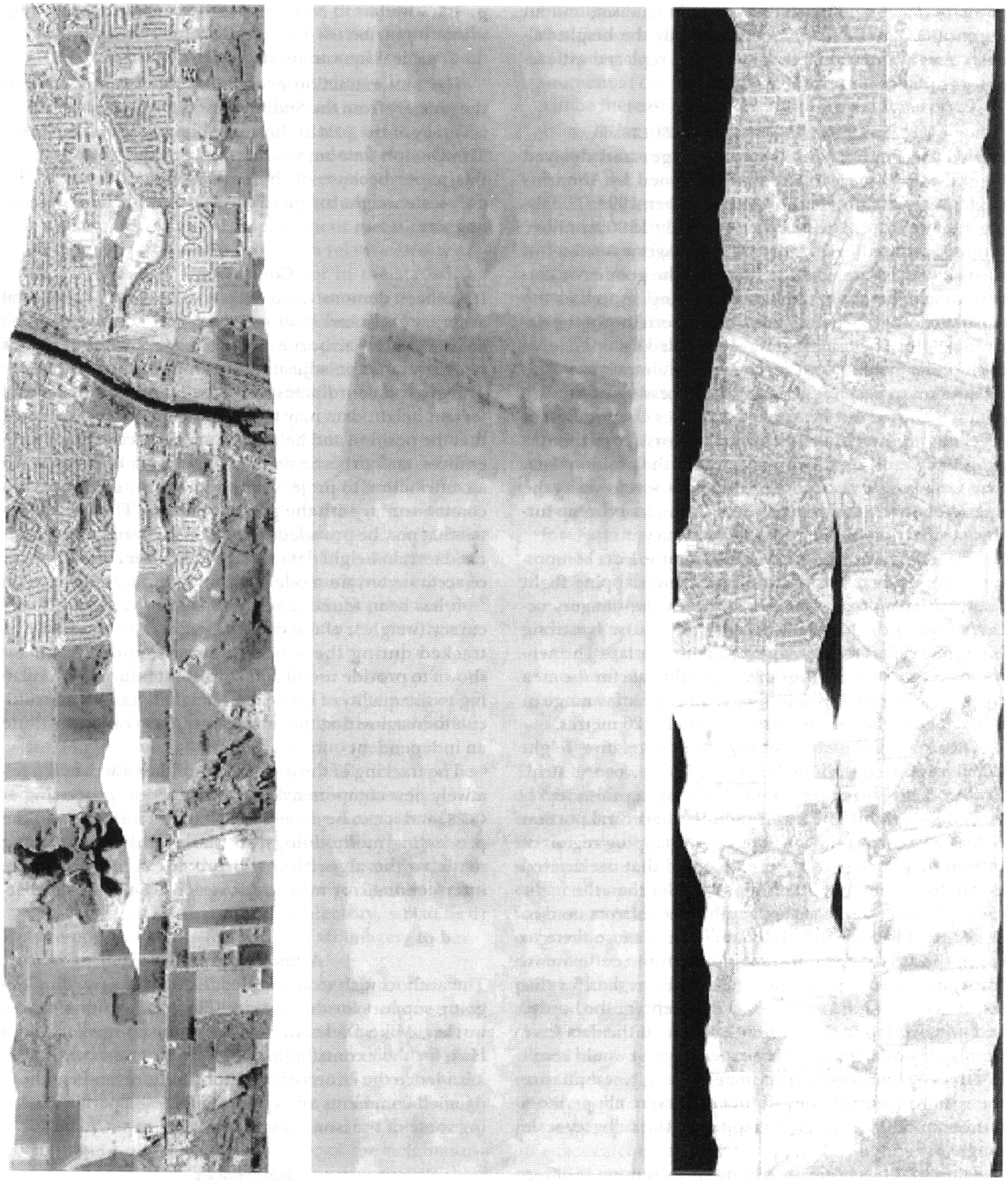

Composite nadir image — *Derived height image* — *Weight of derived height*

Figure 1. Illustration of nadir mosaic, derived height and derived height weight files

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Resume L'incertitude dans les donnée altimétriques déreivées Dans ce chapitre on traite de la détermination de l'incertitude rattachée aux données altimétriques dérivées d'imageries stéréoscopiques acquises au moyen d'un système imageur électro-optique numérique multispectral aéroporté. L'objectif global du logiciel décrit était la préparation de données à leur introduction dans les systemes d'information géographique et l'obtention de coordonnées-terrain de la plus grande exactitude possible pour ces données. Le présent chapitre fournit un bref aperçu des procédures qui ont été appliquées pour le traitement des imageries brutes et des données accessoires du système de navigation par inertie pour la compensation photogrammétrique, la correction géométrique et l'extraction de l'altitude du terrain; on y illustre de plus les résultats obtenus au moyen d'un ensemble de données representatif. L'un des produits ultimes fournis par les systèmes logiciels de traitement est une mosaïque d'ortho-images basée sur les visées des nadirs et les données altimétriques générées d'après l'imagerie stéréoscopique.

On discute dans ce chapitre les méthodes et les procedures actuellement mises au point au Centre canadien de télédétection pour suivre ou reporter les exactitudes relative et absolue des produits de donnees dérivés depuis les données brutes jusqu'aux produits finals. En conclusion on présente à titre d'exemple une imagerie traitée et les données altimétriques dérivées avec une mesure de confiance ou d'incertitude des altitudes dérivées.

Zusammenfassung Verfolgung der Unsicherheit beziiglich abgeleiteter Hohendaten Dieses Kapitel behandelt das Verfolgen der Unsicherheit hinsichtlich aus Stereobildern abgeleiteten Höhendaten; diese Bilder wurden von einem elektro-optischen, digitalen, multi-spektralen Bord-Abbildungssystem geliefert. Der Gesamtzweck der beschriebenen Software besteht darin, die Daten zur Eingabe in Geographische Informationssysteme vorzubereiten und Geländekoordinaten der Daten mit größtmöglicher Genauigkeit zu liefern. Das Ziel des Kapitels ist es, einen kurzen Überblick über die Verfahren zu bieten, die bei der Verarbeitung der Rohbilder und der zusätzlichen Daten eines Trägheits-Navigationssystems angewandt werden, urn die photogrammetrische Einstellung, die geometrische Korrektur und die Geländehohen-Bestimmung mit Rilfe der Digitalbildern durchzuffihren sowie Beispiele für die Ergebnisse anzufuhren, die durch die Verarbeitung eines repräsentativen Datenbestands gewonnen wurden. Eines der Endprodukte, das aus den Software-Verarbeitungs-Systemen hervorging, ist ein Mosaik von Orthobildern unter Benutzung von Nadir-Luftbildern und von Höhendaten des Geländes, die von den Stereobildern geliefert wurden.

Das Kapitel befaß sich mit den Methoden und den Vorgängen, die vom Canada Centre for Remote Sensing entwickelt werden und zum Ziel haben, die absolute und relative Genauigkeit der abgeleiteten Datenprodukte von dem Rohdaten-Stadiurn bis hin zu den Endprodukten zu verfolgen bzw. zu tragen. Das Referat schließ mit einem Beispiel von verarbeiteten Bildern und abgeleiteten Höhendaten und mit dem Vertrauensmaß oder der Unsicherheit bezüglich der abgeleiteten Rohe.

Resurnen Rastreo de la incertidumbre en los datos de altura de terreno derivados Este capítulo discute el rastreo de la incertidumbre en los datos de altura de terreno derivados de la imagen estéreo obtenida mediante un sistema aerotransportado de toma de imágenes multiespectral digital electroóptico. El objetivo general del soporte lógico descrito es el de preparar los datos para introducirlos en los Sistemas de Información Geográfica y dar las coordenadas de terreno de los datos con la mayor precisión posible. El capítulo tiene como objetivo proporcionar un breve panorama general de los procedimientos que se siguen en el tratamiento de la imagen sin procesar y de los datos de los sistemas auxiliares de navegación inercial, para realizar ajustes fotogramétricos, corrección geométrica y extracción de la altura del terreno utilizando la imagen digital, e ilustrar los resultados obtenidos a partir del procesamiento de un conjunto significativo de datos. Uno de los productos finales de los sistemas de procesamiento del soporte lógico es un mosaico de imágenes ortogonales que se obtiene utilizando

visiones nadirales y datos de altura de terreno generados por la imagen estéreo.

El capítulo discute los métodos y procedimientos que se están desarrollando en el centro de Teledetección de Canadá para rastrear o trasladar la precisión absoluta o relativa del producto derivado de los datos, de los datos sin procesar al producto final. El trabajo concluye con un ejemplo de algunas imágenes procesadas y datos derivados de altura de terreno, junto con las medidas de confianza o incertidumbre de la altura derivada.