Analysis of the Characteristics and Orientation of Linear Array Stereo Imagery from Satellite Sensors

by

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ABSTRACT.

The study of the thesis is the orientation and analysis of linear array imagery from satellite platforms. Several types of space borne sensors have been considered for the production of new map products. SPOT data is at present the most commonly used type of imagery, mainly due to its high resolution CCD sensor, high stability, world coverage and availability. However, other types of linear array sensors have been under study for future space programs, and these are studied in this thesis.

An overview of different methods of orientation of SPOT stereopairs is given and the advantages and disadvantages of these models are discussed. The weaknesses of across track stereo imagery obtained with SPOT data are pointed out and the use of along track stereo imagery is discussed.

The applicability of the different orientation methods to other types of linear array imagery is studied. Existing methods being used for the orientation of along track linear stereo imagery are assessed and a critical view is presented. Based on this study, an orbital approach is developed for the orientation of along track stereo imagery. This model makes use of an additional parameter describing the relative positions of different images taken during the same orbit, reducing the number of control points needed by half.

Data was simulated for the tests because no real data is yet available, and the simulation method is described. SPOT data was used as the raw data to simulate imagery of future along track linear array cameras.

Tests were carried out to evaluate the precision expected to be obtained with along track stereo imagery from future sensors such as ASTER, OMI and OPS. Tests on blocks of linear stereo imagery considering simultaneously across and along track stereo imagery were also carried out and the performance of the algorithm evaluated.

The effect of the characteristics of the images forming a stereopair, and of the conditions of orientation of that stereopair, on the accuracy of the model after orientation was tested for several cases.
High correlations between the orientation parameters result in problems in stability in the modelling algorithm. A study of the model variations due to small variations of the orientation parameters was made and weighting matrices were adopted to reduce the effect arising from these correlations. However, the use of weights did not improve the orientation in the case studies, as theoretically expected. Research is advised in this subject using data from future linear array sensors.

Early tests carried out using conjugate points to reduce the number of control points required during the orientation process of SPOT imagery are presented. Similar tests were carried out with simulated along track stereo data. Problems of convergence were found when using conjugate points and a reduced number of control points during model orientation.
To the memory of my father.

Tudo o que sonho ou passo,
o que me falha ou finda,
é como que um terraço
sobre outra coisa ainda.
Essa coisa é que é linda.

Por isso escrevo em meio
do que não está ao pé,
livre do meu enleio,
sério do que não é.
Sentir? Sinta quem lê!

Fernando Pessoa
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Chapter 1
Introduction

1.1. Linear array imagery from satellite sensors

Since the early use of photogrammetric techniques in map production, the main data source has been aerial photography. Historically, technology and instrumentation was developed to allow stereo restitution from this type of data. However, maps are presently being produced for a more diverse range of uses, demanding more diverse information than that being considered for classical products. As a consequence, classical map production systems no longer meet the current demand for map production and revision [Welch, 1980; Rochon and Toutin, 1986; Dowman and Peacegood, 1989].

Several studies have been carried out to evaluate the extent of the classical limitations [Hoeven, 1989; Munier and Rivereau, 1989] and possible suggestions for improvement. Map products derived from satellite data are proving to meet most of the required specifications [Gugan and Dowman, 1988a; Hartley, 1988]. For these reasons, new map products are also under consideration by some institutions [Albertz et al., 1992; Solberg, 1992; Akiyama, 1992], with improvement in mapping costs as well [Hoffmann, 1992; Lenzen, 1992].

The use of computer aided instrumentation in photogrammetric systems enables the orientation of almost any type of imagery. Orientation algorithms specially written to meet specific geometric characteristics can be added to allow three dimensional visualisation from non-frame photography [Hoeven, 1989; Paderes and Mikhail, 1983].

It is known that satellite platforms are more stable than lower altitude platforms. Therefore, it is easier to orientate imagery taken from satellite than from aerial
Chapter 1 Introduction

platforms, as there are fewer effects to consider from the attitude of the platform [Paderes and Mikhail, 1983]. This allows the reconstruction of the imagery platform movement at time of acquisition with a reduced number of orientation elements. Moreover, orbital parameters have been commonly adopted to describe the position and movement of the satellite successfully.

Charged Coupled Devices (CCD) placed in linear arrays have been used advantageously to extract imagery from satellite platforms. This technology has the advantage of not introducing any moving parts to the imaging system, since the image is acquired as a direct consequence of the satellite’s movement in its orbit. This technique maximises the exposure time, and records the imaged data directly in digital form [Welch and Marko, 1981], e.g., the French Satellite Pour l’Observation de la Terre (SPOT) sensor has been using this type of technique for several years now with successful results [Veillet, 1988; Veillet, 1991; Dowman et al., 1991].

SPOT data, due to its geometric characteristics, and very stable platform, has imagery qualities that allow it to be used for various purposes [Hartley, 1988; Day and Muller, 1988; Styles, 1987]. Its stereo capability and very high resolution are the most important characteristics for map production. The precision of the three-dimensional information that can be extracted from SPOT stereomagey has been a subject of evaluation by several researchers. The studies carried out on this subject agree on SPOT data suitability for the production of map products at scales smaller than 1:50,000. It is also agreed that although SPOT imagery is not suitable for map production at scales larger than 1:50,000, it may still be suitable for map revision at these scales [Rodriguez et al., 1988; Grabmaier et al., 1988; Paulsson, 1992; Malmström and Engberg, 1992; Atilola, 1992].

Several other types of products have been based or captured by the SPOT sensor, with advantages on reduction of production costs, and on production delays, and the added capability of data integration with images from other sources and geographic information systems [Foin, 1988; Akiyama, 1992; Albertz et al., 1992]. Published information suggests that these image maps are particularly useful in areas where no up-to-date mapping exists, particularly for coverage of very large regions [Munier and Rivereau, 1989].

The excellent performance and quality of the SPOT sensor has inspired several institutions to construct other sensors using the same type of technology while
simultaneously trying to solve some of the problems encountered with SPOT imagery [Diner et al., 1990; Arai, 1991; Lanzl, 1986]. The oblique, or across track viewing capability of the SPOT sensor considerably reduces the time required to access a given area or to obtain complete stereo coverage of a country. However, the operational application of SPOT imagery in cartography has not reached its full economical importance [Munier and Rivereau, 1989; Hartley, 1988].

Some of these restrictions are related to conflicts between current methods, old specifications and the user needs, as well as the sensor’s ground pixel resolution. However, the main problems for the use of SPOT data are related to the time delay between the two images taken to form a stereopair. The two images are usually taken several weeks or, sometimes, months apart. Differences may occur due to crop growth between the imaging times, changes caused by human intervention and even due to the sun’s illumination. The images are also usually taken from opposite sides of the object, one from the east and the other from the west. Consequently, the illumination changes thus causing difficulties in forming and interpreting the terrain model [Kauffman and Haja, 1988; Hoeven, 1989].

To avoid these problems, other types of sensors have been considered for future Earth Observation Missions. These still use linear arrays of CCD sensors mounted on satellite platforms to get the best geometric quality akin to that from SPOT. However, the linear arrays are mounted such that they will image the ground with a forwards/backwards viewing geometry. This supposedly solves the disadvantages found in SPOT across track stereomodels [Diner et al., 1990]. In an along track system configuration the images forming the stereo model are taken only a few seconds or minutes apart, with approximately the same illumination. The imagery is also acquired faster because both images of the stereopair are taken during the same orbit.

An orientation model describes the viewing geometry of the imagery in space, and depends on various geometric distortions, which may be divided into two categories. The first group includes the scan-positional parameters, panoramic distortions and the effect of relief, which can be corrected by a priori knowledge of the line scanning system. The second group includes the residual distortion in the data, after a correction for known errors. These errors are mainly due to variations in the altitude and velocity of the platform and may be reduced by use of ground control points (GCPs) [Dowman and Coyle, 1984].
Models already developed for the orientation of across track imagery (ACTI) such as SPOT imagery may still be used to orientate along track imagery (ALTI) with some adjustment. In by then considering the characteristics of this new geometry it is possible to reduce the requirements needed for its orientation [Ebner et al., 1988; Colvocoressess, 1982].

Images of an along track stereo model are acquired during the same orbit, having some common orientation parameters. An orientation algorithm can thus be developed to orientate this type of imagery with a further reduction of the ground control needed. This may be done using some correctly chosen additional parameters. The introduction of the extra parameter or parameters may also introduce high correlations between the orientation parameters. To enable an understanding of these correlations, a proper study and analysis of linear array imagery (LAI) must first be carried out (Chapter 2).

1.2. Scope of the thesis

1.2.1. Objectives of the study

Several models have already been developed for the orientation of SPOT imagery. These are analysed in order to identify their advantages and possible application to model other types of linear array imagery from satellite platforms. This analysis was performed to study the suitability of the different existing orientation models of ACTI to orientate ALTI.

The effects suffered by linear array imagery due to variations in position and attitude of the platform will be assessed. The results from this study will be compiled and a suitable general solution presented.

Thus the main objectives of this work are:

1. To design an algorithm capable of orientating blocks of combined across and along track linear array imagery from satellite sensors. The final algorithm should be
capable of orientating blocks of stereo imagery with a minimum of control, in order to reduce the costs of any product derived from the imagery.

2. To forecast the accuracy to be expected from modelling future ALTI to be acquired from sensors such as ASTER, OMI and OPS. These results are to be compared with existing models obtained from SPOT data.

3. To assess the advantages of the introduction of along track capability to future SPOT sensor missions. This study will be carried out by comparing the orientation of simulated ALTI with the results achieved orientating existing SPOT data.

4. To study the influence of the control distribution over the model on the accuracy of the orientation. The results obtained by using pass-processing techniques with the same algorithm are to be analysed. The accuracy achievable with strips of data acquired over different time spans, using additional on-board measurements, or not, is to be studied.

5. To assess the advantages of the use of conjugate points on the orientation of ACTI and ALTI. The use of conjugate points to improve further the absolute or only the relative orientation of the model is also to be studied.

6. To study probable improvements occurring from the use of weights during the orientation process. Different weighting methods are tested.

1.2.2. Main parts of the thesis

The study had to be carried out in various phases in order to achieve the objectives previously described.

First, the characteristics of linear array systems are described in chapter 2. The pushbroom system is reviewed and the effects of the terrain relief on linear array imagery are studied. With reference to these effects, the stereoscopic capabilities and characteristics of CCD imagery are inspected. The SPOT satellite characteristics and several modelling processes are presented. The geometric characteristics of SPOT data are assessed, and different approaches to model its stereo imagery are compared. The suitability of an orbital approach method for the orientation of along track stereo
imagery from satellite sensors is reviewed and future along track satellite sensors are presented.

In the third chapter, an orbital model developed for the orientation of linear array stereo imagery is presented in detail. The model accepts both ACTI and ALTI, and an additional parameter is described for the orientation of along track stereo pairs, which reduces the number of control points required. The correlations occurring from the use of this extra parameter are described and a method of weighting the orientation parameters is adopted to constrain the solution. In this chapter the requirements for the orientation of blocks of linear array imagery and pass-processing are presented. The procedure for the simultaneous orientation of ACTI and ALTI is described and the use of header data is discussed.

The fourth chapter concentrates on the simulation algorithm developed to create data for testing linear array models. The simulation process is described in detail and its use in the thesis is justified because no real data existed for the tests. Real data that served as a basis set for the simulation is presented and the process of extension of the data set to form a long strip is explained. The data simulation is also validated in this chapter by comparison of SPOT real and simulated models.

The accuracy of the future sensors ASTER, OMI and OPS is forecast in chapter five. The accuracies of these models are compared to the accuracy of the existing SPOT models and to the theoretical SPOT-like sensors with along track capability. The SPOT-like sensors are used to forecast the accuracy of a SPOT sensor if equipped with an along track acquisition system. This also helps distinguishing between the differences in accuracy resulting from the different geometry or from different pixel resolution, viewing angle or other physical characteristics of the sensor. The results from the orientation of blocks of linear array imagery are also presented in the same chapter. Hybrid models formed by orientation of OMI and SPOT simulated data, and OMI and ASTER simulated data are studied.

The sixth chapter reunites the tests performed to study the effect of the data characteristics on the accuracy of the models. The SPOT and OMI simulated data form models with different characteristics, and were chosen to represent across and along track imagery, respectively. The effect of errors of identification of the control on the imagery or on the ground on the final accuracy of the model are evaluated. Similar studies are carried out to evaluate the influence of the length of the model, the B/H, and
of the number and distribution of the control to the final accuracy of the model. In these
tests, improvements of the accuracy of models orientated using the attitude data as
auxiliary information are also assessed. The capability of the algorithm to orientate
discontinuous across and along track data is tested. Possible improvements achieved by
using \textit{a priori} information such as the time of acquisition of the imagery and the position
and velocity of the sensor are also discussed.

Chapter seven is dedicated to the study of the effect of small errors in the orientation
parameters to the model accuracy. This study is performed for the changes in the orbital
and in the attitude parameters. Based on this study, a critical view is taken on the criteria
adopted for stopping the iterative process during the model orientation. The correlations
between the orientation parameters are also analysed in this chapter and the use of a
weighting matrix to control the effect of these correlations is studied. For this purpose,
tests are performed, by forming the weighting matrix with \textit{a priori} information of the
orientation parameters. This is either introduced by the user, or obtained from the header
data.

In the eighth chapter, the algorithm adopted for the introduction of conjugate points
in the orientation process is presented. Tests performed with real SPOT data and with
simulated OMI data are performed. The advantages and disadvantages of using
conjugate points during the orientation process are assessed from these results.

A summary of the work carried out by the author, and of the conclusions obtained are
presented in the ninth chapter. A critical analysis is made on the overall results and
based on this, future work for development of the orientation algorithm is analysed.
Remarks on possible ideal conditions required for a best orientation are discussed.
Chapter 1 Introduction
Chapter 2.
Linear array imagery

2.1. From aerial photography to linear array systems

Classical photogrammetry uses aerial photography with a central perspective geometry for the acquisition of three dimensional information for cartographic purposes. The most important characteristic of aerial photography is the geometric quality of the data, which describes its capacity to give the exact location of objects imaged. The geometric quality of the data depends mainly on the dynamics of image acquisition, on the stability of the image geometry and on the type of pre-processing performed on the raw data. The geometric quality can be further assessed with respect to the accuracy of the shape reproduction and the use of auxiliary data.

As early as 1962, Elms elaborated on the strip camera concept and indicated its advantages over frame cameras as a possible component of an automated mapping system [Elms, 1962; Colvocoressess, 1979]. The strip camera is based on using a line-sensitive film that is moving forwards at a calculated speed, directly dependent on the ground track velocity of the aircraft. However, the use of film is neither very convenient, nor easy to deal with, and the CCD can be used to simplify the imaging systems.

A CCD transforms the incident light into a sampled video signal, which is coded and transmitted electronically to the ground stations. The advantages of using this technology have been recognised by several authors [Thompson, 1979; Gugan and Dowman, 1988b]. CCD arrays can be mounted with different geometries, e.g., linear arrays which eliminate complex mechanisms. High resolution and geometric stability for accurate feature identification and location is achieved using CCDs [Gugan, 1987]. Additionally, the improvement in signal-to-noise ratio is significant, which permits
smaller aperture optics to be used, and a consequent reduction in size and weight of the sensor [Thompson, 1979].

It has been stated by Dowman and Peacegood [1989] and Neto [1989] that the type of data used for any study has influence on the results obtained. Currently, digital imagery is becoming more widely used as a data source. If digital data is required, using digitization becomes unnecessary. The CCD data has the advantage of being available in either digital form or as film positives, for all types of user demands.

The CCD imaging systems may be mounted either on airborne or satellite platforms [Ebner and Müller, 1987]. They may be variously mounted to obtain different viewing modes, from different types of platform. However, CCDs are most often mounted in a linear array configuration. The CCD arrays are mounted in the focal plane of the camera, pointing towards the Earth's surface. Linear array imagery (LAI) is obtained as a consequence of the movement of the satellite in space (§2.3.1).

Several systems, based on digital opto-electronic line scanners were or are in use: MOMS [Hofmann et al., 1980], SPOT [Chevrel et al., 1981], MEOSS [Lanzl, 1986], and OPS [MITI/NASDA, 1990]. Others are proposed for future programs: MOMS-02 [Ebner et al., 1992], ASTER [Arai, 1991], and OMI [British Aerospace, 1991]. Other systems such as STEREOSAT [Welch and Marko, 1981] and MAPSAT [Colvocoressess, 1982] were proposed but were subsequently abandoned, though these systems helped in the implementation of other systems such as the ASTER, OMI and OPS. Linear array sensors mounted in spaceborne and satellite platforms give very high resolution, performance and capabilities, which are still being explored by several centres [Gugan and Dowman, 1988b; Dowman et al., 1991].

2.2. Aerial linear array imagery

Due to its geometric characteristics, LAI from aircraft has been studied since very early days.
The orientation of LAI changes for every line, which makes it less stable than aerial photography. Nevertheless, the continuity of LAI can be used advantageously. Elms [1962] analysed the possibility of extracting three dimensional information from strip-cameras. In the study, he concluded that although the use of the strip camera with conventional plotting systems was not feasible in 1962, it was not impossible to envisage the use of such a camera as part of an automatic mapping system in the future.

Higher altitude platforms are more stable than aircraft and, therefore, linear imagery obtained from space platforms is preferable. Ockert [1960] noted that the end use of the photography as well as the restrictions of satellite operation should influence the choice of these cameras for satellite photography.

The Deutsche Forschungsanstalt für Luft- und Raumfahrt (DLR) is engaged in several stereo scanner projects, of which the MEOSS and the MOMS-02/D2 are three-line array sensors. MEOSS is to be launched on board an Indian satellite mission (IRS-1E) while the MOMS-02/D2 sensor will be part of the payload of the German mission D2 scheduled for a spaceshuttle flight in 1993 [Lehner and Gill, 1992]. The airborne model of the MEOSS camera has been tested and results are presented and commented on in section §2.7. Results obtained with simulated MEOSS and with MOMS-01 data are also presented in the same section of this thesis.

2.3. Satellite linear array imagery

The use of CCD linear arrays instead of frame photography has several advantages for satellite imagery, eg. all the information is recorded digitally and is easily sent to the ground recording facilities on Earth.

With reference to the frame camera, it is interesting to note that the advantages tend to be concerned with metrics while the disadvantages tend to be mechanical in nature [Ockert, 1960; Colvocoressess, 1979]. Likewise, a satellite offers the unique advantage over an aircraft of much greater stability and uniform velocity [Colvocoressess, 1979;
Konecny et al., 1987], since the satellite does not experience changing wind nor downdrafts, and the forces that change its orientation are all internal [Ockert, 1960].

Additionally, the number of ground control points (GCPs) needed to correct a satellite image is much less than that required to correct a corresponding area of aerial photographs. GCPs are very expensive to set up; hence satellite imagery becomes cheaper for production purposes [Swann et al., 1987; O'Neill, 1991; Sharpe and Wiebe, 1991].

2.3.1. Pushbroom imagery

Pushbroom scanning is a term that describes the technique of using the forward motion of a satellite platform to sweep a linear array of detectors orientated perpendicular to the ground track across an area being imaged [Thompson, 1979].

The CCD linear array of detectors is orientated perpendicular to the flight path, and is built in the focal plane of the sensor. As the along track motion scans the projection of the detectors over the scene, the detectors are electronically sampled so that the entire line array is recorded in the time to advance one resolution element. The column position of a pixel is no longer an image coordinate but a measure of time determining the position of the satellite in its orbit. The resulting image formed by successive recorded lines has an approximate parallel plane perspective and is therefore not similar to frame photography.

The imagery obtained during this kinematic process is also referred to in the literature as dynamic [Drescher et al., 1986; Gugan and Dowman, 1988b]. The term dynamic is used to describe variations of the position of the sensor with time. However, these variations are not random, being constrained by the physical process involved. Therefore, the variations of the satellite's position with time are well defined and should be designated as kinematic.

While a long strip of imagery is being recorded, the position and orientation of the sensor in space vary continually. The resulting image has a multiple plane perspective made up of many plane perspective strips [Gugan and Dowman, 1988b]. Most sources of image distortion can be measured during the image acquisition by on-board
instruments or computed from the orbital data after image reception by the ground stations.

In recent years there has been noticeable progress using linear array sensors for digital image recording using the pushbroom scanning mode [Ebner and Müller, 1987]. The precise geometric positioning and high sensitivity of the detectors of these sensors, and the fact that no moving optics are used are the main advantages of these scanning sensors [Thompson, 1979; Hofmann et al., 1980]. The simplicity of the scan mechanism ensures the automatic maximization of the exposure time and an excellent quality along the scan axis [Thompson, 1979; Gugan, 1987]. Improvements in the image resolution occur as a consequence, to which technological progress in manufacturing smaller CCDs also contribute.

2.3.2. Effects of platform movements on the imagery

The platform on which the sensor is mounted has not a perfectly smooth flight path. Deviations from the basic simple flying geometry produce several effects on the imagery [CNES, 1989].

During image acquisition, the successive scanlines recorded by the CCD linear arrays shift westwards as a result of the Earth’s rotation. Additionally, the curvature of the Earth deforms the geometry of images at large viewing angles by about 30%. The line-sampling interval increases with the viewing angle and a variation in the line sampling interval results in an error on the relative location of pixels. The line sample interval varies in direct proportion to the spacecraft altitude, even for viewing directions close to the vertical.

To assess the correlations between the different attitude parameters, the effect of attitude changes on the image geometry of linear sensors has been analysed by various authors [Kruck and Lohmann, 1986; Gugan, 1987; Welch, 1980]. More recently, those effects have also been studied by Westin [1990], and Konecny et al. [1987].

Attitude variations result in changes in the relative positions of successive image scanlines. To study effects of the attitude variations on the LAI, a comparison is made with the effects observed in a frame photograph. This comparison will help an
understanding of the possible correlations between the parameters and enable a correct choice of the parameters to be used in the orientation process.

A frame photograph is a two dimensional data set. Changes in the regions imaged next to the corners of the photograph can be used to identify distortion that might have occurred during film exposure. The effects of position and attitude changes of the platform on a frame photograph are sketched in [Fig 2.1], where \( \Delta x, \Delta y, \Delta z \) represent changes in the position and \( \Delta \varphi, \Delta \omega, \Delta \kappa \), changes in the attitude of the platform. A system of reference is chosen for frame photographs such that \( x \) is in the direction of flight, \( z \) is vertical and directed towards the zenith, and \( y \) forms an orthogonal system with the other two [Fig 2.1].

The reference system adopted for strip photographs is also chosen such that the \( x \) axis is along the flight direction, \( z \) vertical and \( y \) is in the across track direction, i.e., along the array [Fig 2.2]. The angles \( \Delta \varphi, \Delta \omega, \Delta \kappa \) are the pitch, roll and yaw around the axis in the across track direction, the flight direction axis and the vertical axis, respectively.

The pitch angular rate introduces superimposition or a missing portion in the area covered by two successive scanlines. A roll angular rate shifts image scanlines parallel to their own direction, and on this in turn will be superimposed the effect due to the Earth's rotation. The yaw angular rate produces slow rotation of image scanlines.

However, the one-dimensional characteristic of LAI does not allow us to distinguish between the effects of changes of attitude and of position. This problem results in high correlations between the orientation parameters of the image as illustrated in [Fig 2.2]. In contrast to what happens in a frame photograph, in a linear array it is impossible to distinguish between the effects produced by
- a shift in the along track direction and a variation in pitch; and
- a shift in the across track direction and a variation in roll, as shown in Fig 2.2.
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Fig 2.1 - Effects of changes in position and attitude on a frame photograph.

Fig 2.2 - Effects of changes in position and attitude on a linear array.
2.4. Across and along track stereoscopy

2.4.1. Across and along track imagery

In pushbroom systems, the CCD linear array is always kept perpendicular to the along track axis. However, the linear array is not usually pointing straight down to the nadir, i.e. the sub-satellite point. Usually, the viewing positions are backwards and forwards looking, or side looking, and of these, the most common viewing system adopted is side looking. This is obtained keeping the optical plane vertical and the central point of the linear array oblique relative to the nadir [Fig 2.3].

For backwards and forwards looking systems, the optical plane is deviated from the nadir by an angle along the direction of flight [Fig 2.4]. Eventually, a forwards, nadir or backwards looking angle may be added to the side-looking angle to form a combined system.

Fig 2.3 - Across track image acquisition.
2.4.2. Across and along track stereoscopy

A platform may support more than one camera, each being a CCD based pushbroom imager. This strategy provides continuous multi-angle observing, and spatial coverage [Diner et al., 1990].

Image distortions due to terrain relief can be evaluated measuring the parallax on image stereopairs. The stereoscopic parallax is the difference between the observed position of a common point for two images taken from different viewing angles [American Society of Photogrammetry, 1980]. The measurement presumes a knowledge of the platform movements and image geometry to distinguish the effects of relief.

To enable the identification of parallax, different types of imagery have to be considered:
- images recorded by cameras equipped with rotabell mirrors to control the pointing direction, as in ACross Track Imagery (ACTI); and
- images recorded from fixed forwards, vertical and backwards pointing cameras, as in ALong Track Imagery (ALTI).

Stereoscopic pairs may be obtained using side looking imagery by combining data recorded from adjacent orbits [Fig 2.5]. Such a system relies on perspective geometry to develop parallaxes [Welch, 1980].
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Data can be recorded simultaneously with two sensors on the same platform during the same orbit, e.g., one of them looking forwards and the other backwards [Fig 2.6]. It is possible to determine three dimensional object point coordinates and to reconstruct the exterior orientation of such a pair making use of parallel ray geometry [Ebner and Müller, 1987; Welch, 1980].

![Diagram](image1)

Fig 2.5 - Stereopair obtained using side looking imagery.

![Diagram](image2)

Fig 2.6 - Stereopair obtained using along track imagery.

The image will always suffer distortions due to terrain relief. Pushbroom stereopairs are differently affected by the terrain depending on whether they are ALTI or ACTI.
For lateral viewing, the relief introduces a small shift of the point (parallax) only along the linear array [Fig 2.7]. When along track imagery is used, the parallax is mainly
perpendicular to the array system, thus correlated to the time of acquisition of the ground points [Fig 2.8]. Consequently, the line number of a certain point represents the acquisition time as well as the effect of terrain relief.

It has been shown [Swann et al., 1987; Dowman et al., 1991] that the base to height ratio (B/H) of the stereopair is an important factor in the evaluation of the terrain relief. The larger the viewing angles of the images forming the stereopairs, the larger the B/H. Clearly, the effect of relief is larger in images with larger viewing angles, and hence easier to identify. Therefore, better evaluations of the terrain relief can be obtained with stereopairs with larger B/H.

Unlike side looking stereopairs, the line position of any imaged ground point in the image planes of the forwards and backwards pointing cameras is a function of the ground elevation and of the imaging time, resulting in a correlation between these two. Welch [1980] showed that stereopairs may require as long as 90 seconds to 2 minutes to be recorded. Obviously, any variation in the attitude of the satellite over this rather long interval will produce planimetric and vertical displacements. Consequently, the attitude control system is an extremely important component of spacecraft design. The accuracy to which is known the time span between the ALTI images is also very important, since it has the same effect on the imagery as the terrain relief.

The examples given above refer only to image pairs. Some authors [Kratky, 1989a] refer to the advantages of using more than one pair of images for the same area, in order to improve the height information extracted from the model.

2.5. The SPOT satellite

The first Satellite Pour l’Observation de la Terre (SPOT-1), equipped with a pushbroom imaging system, was launched on the 22nd February 1986 by an Ariane launch vehicle [CNES, 1989]. The second in the line, SPOT-2, was launched on the 21st January 1990 and has already totally replaced all the functions of SPOT-1 [SPOT Image and CNES, 1990]. The systems of the two SPOT satellites are similar, for both are
equipped with a side looking pushbroom system. SPOT-2 is additionally equipped with a Doppler Measurement (DORIS) navigation system [Cazenave, 1988]. First evaluations of the SPOT-2 data showed that its quality is similar to that of SPOT-1 [SPOT Image and CNES, 1990].

Since the first releases in 1986, SPOT data has been studied and used for many different purposes [Dowman, 1987; Styles, 1987; Hartley, 1988a; Heipke and Kornus, 1991]. The automated generation of Digital Elevation Models (DEMs) from SPOT images has been a primary goal of several different groups around the world, from private sector companies [Simard et al., 1988; Swann et al., 1987; Vincent et al.; 1988] to mapping organisations [Guichard et al., 1988]. These attempted to use resampled epipolar image data as inputs to the stereomatching process to restrict the research space [Day and Muller, 1988].

Other workers [Dowman and Peacegood, 1989; Hartley, 1988b] have been more interested in evaluating the completeness of terrain information from SPOT imagery for mapping purposes. On this subject, Grabmaier et al. [1988] concluded that morphology is visible in more detail than can be presented in a map at the scale 1:100,000 or 1:50,000. However, it is not considered a reliable source of information for other topographic details. Assessing the SPOT imagery content, Dowman and Peacegood [1989] stated the feasibility of SPOT data for mapping at scales less than 1:50,000, and for the production of some map products at scales slightly larger than this. In summary, SPOT data does not provide enough information for production of maps at scales larger than 1:25,000.

2.5.1. Characteristics of the SPOT system

Details of the SPOT satellite system have been well reported in the literature by Rosso [1978], Chevrel et al. [1981] and CNES [1989].

The main purpose of the SPOT system is acquisition, transmission, pre-processing and distribution of images of the Earth’s surface. The system comprises an orbiting satellite with two identical scanning systems as well as ground facilities for image reception, pre-processing, distribution, satellite monitoring and the preparation of imaging programs [CNES, 1989].
The satellite orbit is a near-circular, sun-synchronous, near-polar orbit at an average altitude of 832 km. The SPOT payload consists of the two identical Haute Resolution Visible (HRV) scanners, magnetic tape recorders (for image data storage) and a telemetry subsystem (for data transmission to ground stations).

The HRV instruments were designed to achieve a multispectral (XS) capability of 20 metres, 10 metre in panchromatic mode (P mode) and an across track pointing capability to provide accessibility, slant and stereo coverage.

The two HRV scanning systems are CCD pushbroom sensors (§2.3.1) that may be operated independently of each other. The CCD detectors are at the end of a Folded Pseudo Schmidt telescope with a focal length of 1082 mm, aperture f/3.5 and a spherical corrector lens. At the entrance of the telescope is the Strip Selection Mirror (SSM), which can be rotated in the across track direction to enable oblique viewing. This mirror is a vital and unique feature of the HRV scanners, which may be controlled from the SPOT ground centres. The mirrors can be tilted out of the vertical in 91 discrete steps of 0.6° up to 27° on both sides of the satellite’s track with a pointing accuracy of 0.05° [rms]. This feature allows the selection of target scenes and the acquisition of oblique images suitable for stereo observation [Fig 2.9].

The SPOT HRV panchromatic sensor has a linear array of 6,000 CCD detectors, each 13 μm in size. The array images a strip of the Earth’s surface 60 km wide and 10 m long, each pixel corresponding to approximately 10 m on the ground (P mode). A SPOT image is built up by combining 6,000 of these linear strips, recorded every 1.5 msec as the satellite moves in orbit, resulting in a 6,000 by 6,000 pixel image [Gugan and Dowman, 1988b]. At 27° from the nadir viewing angle, the scene size will increase approximately to 80 km [Westin, 1990].

Each pixel corresponds to 8 bits of information that are compressed by pulse code modulation into 6 bits for transmission to the ground stations. The recording data rate is 25 Mbits/sec for each HRV. The chosen communication frequency used by SPOT is the X band, which allows the transmission of the data recorded [CNES, 1989]. Throughout the mission, periodic on board calibration of the CCD array is made, the amplifier gain being adjusted by ground command. These adjustments permit compensating for large variations, along each orbit, of the angle of incidence of sunlight on the terrain. The sensitivity of the HRV sensor is such that reflectance steps of the order of 0.5% can be
detected under suitable conditions of illumination, i.e., for the sun 30° or higher above the horizon [CNES, 1989].

Satellite stabilisation is ensured by the Attitude and Orbit Control System (AOCS). The AOCS determines the pointing accuracy of the HRV scanners, and the angular drift rates about the spacecraft's three axes, i.e. roll, pitch and yaw. The ephemeris is calculated every three days, and values are given for each scene to an accuracy of 100m in each direction. The attitude of the satellite is determined to 600m on the ground (0.04°); the change observed during the scene recording is reported as being linear over sections of the scene with a magnitude of 7 to 8 pixels [Dowman, 1987; CNES, 1989].

2.5.2. Stereo capability

The mirror, situated in front of the HRV instrument, allows modification of the look direction, making an across track angle with the vertical that can reach ±27°. It is thus possible to record images of the same portion of the ground at different look angles from different orbits, and hence to record a pair of stereoscopic images [Fig 2.9].

![Fig 2.9 - Stereoscopic capability of the SPOT sensor (after CNES, 1989).](image)
2.6. Modelling SPOT imagery

A mathematical model is necessary to establish the geometry of a single SPOT image or a pair of images. A model includes the position and attitude of the sensor to reconstruct the viewing geometry at the time of scene acquisition, and is in the form of a set of equations, or functions, describing the transformation from image coordinates to ground coordinates, and vice-versa.

Due to its kinematic nature, SPOT stereopairs and pushbroom images cannot be orientated in the same way as a stereopair made with frame photographs [§2.3.2]. The LAI has a distorted multiple plane perspective, and the orientation of the sensor and the attitude of the platform thus varies for each line imaged. The knowledge of the position and the attitude parameters of each image line would be required to obtain a perfect and complete model of the terrain. Such a model is impossible to solve as the number of unknowns would be 6 times the number of image lines, i.e., 3 for the position and 3 for the attitude. This would mean the identification of at least 3 control points per line to solve all the equations. The solution to this problem is to model the platform position and attitude as a function of time. The errors incurred will be due to the type of approximation adopted.

2.6.1. General approaches

Early research into the geometry of kinematic images was carried out by Case [1967] and Salamonowicz [1986]. Studies performed by Case [1967] and Masry [1969] recognised that not all the conventional elements of exterior orientation can be determined. This is mainly due to a lack of distinction between the effects already discussed in section §2.3.2. The exterior orientation of each single line is given by six parameters, as in aerial photography, but the parameters of neighbouring lines are highly correlated. This is especially true if the scanner is mounted on a platform of a high altitude satellite with a geocentric orbit. This was usually overcome by one of two methods, by transforming the kinematic imagery into a series of “instantaneous frame
photographs", or by obtaining some of the orientation parameters from auxiliary data [Konecny et al., 1987].

Since each detector element is looking at a different portion of the Earth at any given time, the Earth’s rotation complicates the epipolar condition. The complication can be overcome by controlling the spacecraft attitude. This description is obviously over simplified; further complications involve such factors as the ellipsoidal shape of the Earth, variations in the orbit, spacecraft stability, and even very large elevation differences. Defining the correct satellite attitude and the rates in yaw, pitch, and roll to maintain the epipolar condition requires high precision mathematical analysis [Colvocoressess, 1979].

For the last 10 years, orbit models for SPOT have been proposed and realised [Chevrel et al., 1981; Guichard, 1983; Gugan, 1987; Dowman et al., 1991]. These can be classified into physical and polynomial approaches. Physical approaches try to model the satellite movement explicitly using orbital elements as unknowns, whereas polynomial approaches attempt to approximate the satellite movement by low order polynomials with unknown coefficients [Salamonowicz, 1986; Heipke and Kornus, 1991].

In the polynomial approach, image points whose corresponding ground coordinates are also known are used to fit the data to the ground using polynomials. However, these are not a proper model of the physical phenomena causing distortions in the raw image data. They can often "misbehave" resulting in a large amount of ground control points being required for satisfactory geometric correction of a scene [Salamonowicz, 1986; Diefallah, 1992]. However, some researchers have been successfully developing polynomial orientation algorithms [Zhong, 1992].

An orbital approach has been used to model the geometry of kinematic imagery by Paderes and Mikhail [1983]. As the satellite is nominally pointing towards the centre of the Earth, this method uses the orbital parameters of the sensor during the period of image acquisition and obtains the six elements of exterior orientation from some of these parameters. Salamonowicz [1986] extends this geometric model by finding the parameters of three additional sensor rotations, and rates of change of these rotations, which are applied to the satellite attitude.
Some models introduce additional condition equations to reduce the high correlations in the models. The use of very low correlated orbital parameters avoids the correlations between the unknowns while still forming an approximate functional model. Moreover, some correlation can also be avoided making use of a priori information. This is usually given by the header data, which gives information recorded on-board the satellite. For SPOT data, the combination of the known attitude offset and errors in the predicted orbit results in an rms deviation of around 400m between the true and the predicted scene positions [Westin, 1990]. This information may be used to set an initial approximate model orientation and eventually reduce the number of control points needed during the orientation process.

Reducing the number of control points required represents savings in the time needed for control selection: an effort which is both tedious and a potential source of error. Methods that model the satellite motions and imaging systems illustrate the feasibility of correcting an image with only a few ground control points [Friedmann et al., 1983]. An alternative approach to this problem was given by [Paderes and Mikhail, 1983] and more recently by [Gugan and Dowman, 1988b], [Guichard and Pikeroen, 1988], [O’Neill and Dowman, 1991] and others [Dowman et al., 1991].

2.6.2. Gugan-Dowman’s approach

The Gugan-Dowman model was one of the earliest SPOT models to be described and implemented on photogrammetric instruments for practical use [Gugan, 1987; Gugan and Dowman, 1988a; Gugan and Dowman, 1988b]. Stereopairs of SPOT imagery are orientated using an orbital space resection approach. Each image is orientated separately making use of the Eulerian orbital parameters to describe the position of each orbit in the geocentric coordinate system. Like all the other models for SPOT imagery, the line number is the reference for time variation and the dimension of the line coordinate is zero for coplanarity purposes.

To run the orientation model, the sensor pointing angle is the only value required from the SPOT header data. The program considers fixed values for the along track sensor offset, the orbit eccentricity, and the rates of change of true anomaly and the longitude of the ascending node. The orbital unknowns considered during the orientation
process are the longitude of the ascending node, the orbit inclination, the semi-major axis and the true anomaly of the central line of the image.

Attitude variations are modelled using a set of low-order polynomials. A linear attitude model considers the six angular parameters for pitch, roll and yaw and their linear change rates, and introduces six additional variables to the orientation model. A second-order attitude variation model is optional.

The stereomodel is set up using the collinearity equations approach and incorporates the parameters mentioned above. A numerical approach is used for differentiation to solve the non-linear equations involved during the orientation process [Gugan and Dowman, 1988b].

If a linear attitude variation model is considered, the number of unknowns is 10. In this case, a minimum of 5 control points per image is required for a rigorous solution. Six control points give a solution with some redundancy. A second-order attitude variation model increases the number of unknowns by 3, requiring at least 7 control points per image. When 7 ground control points are used, typically, the resulting model has absolute rms residuals of 15m in plan and 8m in height.

2.6.3. Guichard’s approach

Guichard’s model was adopted at Institut Géographique National (IGN - France) for the orientation of SPOT data. Guichard’s approach is claimed to be a simple, fast and efficient method to model SPOT imagery [Guichard and Pikeroen, 1988]. The tests performed by IGN using this approach produce the best results to date [Dowman et al., 1991].

The formulation of each viewing system is a physical modelling directly inspired from the models used in aerial photogrammetry [Rodriguez et al., 1988]. It considers all orbital perturbations acting on the satellite as a scene is being imaged, including the high frequency rates of change of attitude recorded by the satellite measurement system [Guichard, 1983]. The model uses the ephemeris and the attitude data to compute the approximate position of the satellite and the orientation of the viewing instrument at every instant [Rodriguez et al., 1988].
A least-squares adjustment of the two images of the stereopair is performed employing measurements of both ground control points and conjugate points. Conjugate points contribute with two pairs of image coordinates for which ground coordinates are unknown [Rodriguez et al., 1988].

The measured image coordinates are first corrected for pitch, roll and yaw effects. Then, the position and velocity parameters extracted from the SPOT header are transformed into orbital parameters, and two collinearity equations are introduced for each control point used. The model is formed via a similar approach to that of Gugan-Dowman, i.e., it also sets the line coordinate to zero for coplanarity [Guichard and Pikeroen, 1988]. The ground coordinates of the points are obtained by computing the latitude and longitude of the sensor for one specific time, by computing the position of the sensor in each orbit for that time and by making use of the knowledge about the sensor geometry [Veillet, 1991]. Veillet [1991] stated that the use of constraints during the orientation process keeps the orbit corrections within CNES specifications.

Unfortunately, publications relating to Guichard's model [Guichard, 1983; Guichard, 1986; Guichard and Pikeroen, 1988] are inexplicit, and present very complex formulae whose parameters are very poorly documented.

The IGN software, running on a VAX 730, is able to handle strips with or without ground control information [Veillet, 1991]. The SPOT models obtained without ground control points rely entirely upon the on-board measured data. Typical results reported to be achievable by this method are rms of 9.1m in plan and 5.2m in height for a single SPOT scene.

2.6.4. Kratky's approach

The Kratky model is also a collinearity based approach, but it does not consider the information given by the SPOT headers. It uses the principle of an extended bundle formulation, which is applied to the ground control points and additional intersection points.

The method considers 28 unknown parameters for the orientation of a stereopair. The sensor position in the geocentric coordinate system is described by a set of three second
order polynomials. The sensor attitude is described by a further set of three quadratic polynomials dependent on time. Four additional parameters are considered to compensate for the lack of calibration information for the HRV sensors [Kratky, 1989b].

Twelve constraining equations are added to the solution to keep the sensor orbital parameters within specified statistical limits. Every ground control supported by three coordinates contributes to the solution with four collinearity equations. Five control points and two intersection points are needed to orientate a strip of stereo imagery with no redundancy in input data. The attitude model may be simplified by just considering first order polynomials. In this case, four control points would suffice to orientate the model [Kratky, 1989b]. Typical rms obtained using this model are in the order of 21m in plan and 17m in height.

The low accuracy of the models found using this algorithm may be due to misbehaviour of the polynomials, and/or to the lack of fitting of these polynomials to the orbital parameters.

2.6.5. Picht’s approach

The SPOT sensor model developed by Picht at Hannover is part of the BINGO program system, which supports a few other sensor systems including central perspective aerial photography [Hoeven, 1989].

First, the algorithm uses the SPOT ephemeris data to set up a rough camera model. The sensor positions given in the header data are transformed into an appropriate local coordinate system using a set of 6 polynomials. The higher order coefficients of the polynomials are a function of the local coordinate system adopted.

Next, the BINGO software calculates the image distortions by generating a correction grid, which is applied to the image coordinates. Two grids are generated for both the left and right images: one at the lowest possible ground level and the other at the highest possible ground level. Then, the image coordinates are corrected by an on-line loop program that reduces the central perspective geometry from the restitution system to the SPOT geometry. Beside the reduction from central perspective geometry to the scanner geometry, the grids also account for the distortions caused by angular drift rates.
Additional parameters are added to take care of the distortions caused by the deviation of the satellite from its expected orbit, irregular accelerations, the angular drifts rates of the orientation angles, and the rotation of the Earth [Picht, 1991]. During the bundle adjustment highly correlated parameters are eliminated, with the remaining parameters being entered into the computation of the correction grid. Additionally, geoid undulation can be used for corrections when available [Hoeven, 1989]. However, no information was found on the performance of this feature.

The BINGO SPOT sensor model is able to orientate strips of SPOT imagery with a very small number of control points. An orientation with 2 control points gives rms in the order of 14.0m in plan and 10.0m in height [Dowman et al., 1991].

2.6.6. Haan’s approach

Haan’s model was implemented at the “Politecnico di Milan” and is yet another model that makes use of the header data to orientate SPOT stereo imagery. Haan’s approach considers the following four coordinate systems: the geocentric, the local orbital, the attitude and the instrumental reference systems. The model first converts the image coordinates measured into a set of coordinates in the instrumental reference frame of time, estimated from the line number and the imaging time of the scene centre. A set of three rotations is computed to transform coordinates from the geocentric system to the instrumental reference system. The satellite's initial position, the coefficients of attitude functions and the instrument settings are the unknowns of the model. The imaging time of scene centres, the satellite ephemeris, the error attitude velocities and the instrument settings are the data used from the header. Pitch, roll and yaw are estimated for each point by cubic spline interpolation [Haan, 1991].

Some constraints were introduced to this method. A shift in the satellite's orbit is highly correlated with a shift in the value of the attitude angles. Leaving the attitude functions completely free causes instability in the solution. Pseudo-observations where pitch and roll are initially set to zero are therefore introduced, keeping the error angles close to zero. The second constraint consists of assigning the initial position vector to that given by the header data [Haan, 1991]. This model only requires 2 ground control points to set up a stereo model with low residuals.
2.6.7. Westin's approach

Westin's model also uses the SPOT header data to reduce the number of ground control points required to form a stereo model. The position of the satellite and its motion in space are initially estimated from the ephemeris [Westin, 1990]. The satellite's attitude is computed indirectly from the SPOT header. The on-board measurements of pitch, roll and yaw are used to compute a set of variograms. A set of functions describing the attitude variation as a function of time is then computed using those variograms [Westin, 1991a]. The variogram models trends in the attitude variation of the sensor and thus enables an accurate reconstruction of long orbit segments by use of the raw attitude data given by the SPOT headers.

Later, the model is improved by using additional information obtained from ground control points. Some constraints are used initially to keep the solution within specified values. The algorithm is formulated so that it can orientate both continuous and non-continuous strips of SPOT imagery making use of pass processing and extrapolation techniques [Westin, 1991b]. A set of parameters describing the position and attitude is introduced to the first line of each new scene, and the orbital orientation parameters are set the same for all the scenes acquired during the same orbit.

The model has an orbital formulation similar to Gugan-Dowman's model, and makes use of the header data as initial information to construct the attitude variograms of the sensor. This model is of potential use for orientating long strips of imagery which may or may not be continuous. Typically, this model requires two to three control points to form a stereo model with rms of less than 15m over a strip of 6 scenes.

2.6.8. O'Neill-Dowman's approach

The O'Neill-Dowman's model has the advantage of being almost totally independent of measurements made by an operator. Although easily understood algorithms are used, the model is quite complex. While this approach works well, it does require extensive computation in the optimization process.

The O'Neill-Dowman's model is essentially based on the information given by the SPOT scenes headers. The model is a numerical approach that builds orbit segments for
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the sensor in the image acquisition period for both images in the stereo scene, using the spline interpolation method [O'Neill and Dowman, 1991].

The process of splining enables both the orbit position and velocity vector to be defined as a vector function of absolute time. A first order attitude triad is first computed describing the variation of position of the satellite in space. The attitude ephemeris is then used to apply first order corrections to this rough attitude triad.

A first orientation matrix is obtained from this step, which transforms a reference space to another in which the sensor-ground system lies. A further correction, which takes account of the sensor pointing angle, is determined by bilinear interpolation of the supplied nominal look angles for the first and last sensor of the pushbroom sensor array. The ground intersection itself is accomplished by finding the position along the vector equations of a complementary ray pair, for the shortest vector perpendicular to both ray vectors. This is found by applying Gaussian elimination to a set of linear equations.

Ground control points may be used to refine the absolute attitude calculated. A zeroth order camera model yields ground positions that are related to a set of corresponding check points by a linear shift vector. Refinement of the absolute orientation is accomplished by minimising the linear shift vector for a set of ground control points interactively, with respect to the sensor position and orientation, and possibly additional variables. The optimizer used is based upon Powell's multivariate conjugate direction method [O'Neill, 1991]. This method is capable of approximate rms of 13m in plan and 10 m in height using 3 ground control points per scene [O'Neill and Dowman, 1991].

2.6.9. Comparison of the various methods of orientating SPOT data

The Organisation Européenne d'Études Photogrammétriques Expérimentales (OEEPE) made a series of tests to assess the different characteristics of the several existing methods of orientation of SPOT data and to compare the achievable accuracy by each approach. A few centres were given the same set of SPOT data with annexed instructions on specific pre-defined tests. Hence each centre was to perform the same bench mark tests using the same control data.

Several sets of results were already available from other workers, prior to the commencement of the OEEPE test [Gugan and Dowman, 1988a; Hartley, 1988b;
Kratky, 1989a; Rodriguez et al., 1988]. These results, however, had all been obtained under different conditions, i.e. different models, using different data sets, orientated with different control number and different distributions of the control over the model. These differences in the initial conditions of the tests made it impossible to compare accurately the different approaches. Thus, there was no conclusive analysis for the various characteristics of the different methods adopted.

Using the same data sets and the same control, the OEEPE test enabled a comparison of the different available models to orientate SPOT data. The results of these tests were published in the OEEPE Official Publication No 26, after being presented and discussed in October 1989 at a workshop held at University College London. One sample of the results obtained is plotted in Figs 2.10 and 2.11, including data extracted from Dowman et al. [1991] and O'Neill and Dowman [1991].

The main conclusion from the results obtained is that it is possible to extract fairly accurate height information from SPOT models. All the approaches achieved better precisions in height than in planimetry when compared with check control. It was stressed at the OEEPE workshop that these results were due to the across track geometry of the SPOT sensor and a high B/H, ensuring a high precision in height.

Most of the models presented make use of the orbital parameters to describe the kinematics of the sensor position during the image acquisition. Several authors justify its use to reduce the number of unknowns to a minimum and to avoid correlations between the parameters. Algorithms using the orbital parameters are more stable and the observation equations are easily adapted from the collinearity equations used for classical frame photography [Kruck and Lohmann, 1986; Gugan, 1987].

Except for the Gugan-Dowman and Kratky models, use is made of the header data. The main disadvantage of the former is that a larger number of control points is required to orientate the model. A minimum of 6 well distributed control points are necessary for a reasonably good precision model. It may be possible to orientate the models with fewer ground control points, also reducing the number of orientation parameters considered. In this case, some parameters are considered fixed and consequential, the final orientation is poorer.
Chapter 2 Linear array imagery

Fig 2.10 - RMS residuals in height obtained by different models during OEEPE test.

Fig 2.11 - RMS residuals in planimetry obtained by different models during OEEPE test.
From analysis of the results obtained during the OEEPE tests, it can be inferred that the use of the header data information allows the orientation of the same models with less ground control points. Further it was observed that better results were obtained by those models using constraints during the orientation process.

The IGN results had the lowest residuals, which may be justified by the use of conjugate points during the orientation process as considered by Guichard’s approach [Veillet, 1988; Veillet, 1991].

In summary, all the models achieve accuracies below 20m in 3D when as many as 6 control points are used for the orientation. Below six ground control points, the accuracy of the models is highly dependent on the characteristics of the approach adopted. The main feature contributing to obtain a reasonably stable model with fewer than six control points is the use of the header data file.

2.7. Along track satellite imagery

2.7.1. Along track versus across track imagery

SPOT imagery has been extensively explored and some of its disadvantages have been reported [Kauffman and Haja, 1988]. The main disadvantages of SPOT images are more to do with the characteristics of side looking viewing mode, than any other sensor characteristic. The problems fall into three categories as follows:

- The across track stereo capability may result in a time delay in the acquisition of the stereopairs of days, weeks or months. The resulting scenes may appear quite different due to seasonal variations and sun-angle changes;

- Off-nadir viewing often results in different brightness of the same ground areas between the two views, due to the relative position of the sensor to the illumination direction; and
- Shadows visible in the imagery have different orientations in the two images, which hinders the stereo observation.

Almost all of these disadvantages for side looking viewing geometries can be minimised by along track sensor systems. However, to extract three dimensional information from along track stereo pairs, care must be taken to avoid high correlation between the terrain relief and some of the orientation parameters. For example, some of the attitude parameters presented in §2.3.2 have the same effect on the imagery as the relief [§2.4.2].

Along track systems provide continuous multi-angle imagery with stereo imaging capability supplemented by the radiometric measurements [Diner et al., 1990]. Multi-angle observation allows the acquisition of data without gaps in spatial coverage.

For these reasons, along track stereo imagery has been of importance for a considerable period now.

2.7.2. Experience with along track imagery

Camera systems with along track capability have already been mounted on spaceborne platforms. Further along track camera systems are under development for future launch.

Kratky [1989a] mentioned that a third image of the same area if added to the stereoscopic pair, will construct a more robust model. This may eventually improve the determination of height. Such opto-electronic three line camera systems contain three linear array CCD sensors in the focal plane of the objective, each orientated perpendicular to the flight direction. Within each read cycle number, three sets of images are registered by the three linear arrays, using the pushbroom principle. Each object is imaged three times: first by the forward looking sensor, second by the nadir looking and last by the backward looking sensor [Fig 2.12.].
The Monocular Electro Optical Stereo Scanner (MEOSS) and the Modular Optoelectronic Multispectral Scanner -01 (MOMS-01), are equipped with a three and a two line camera system, respectively, and have been used for some experiments [Lanzl, 1986; Ebner et al., 1988]. The MOMS-02/D2 will also be equipped with a three linear along track array system [Ebner et al., 1992]. The success of these preliminary experiments has induced other along track systems to be developed.

The Multi-angle Imaging SpectroRadiometer (MISR) instrument is a candidate for the first series of NASA Earth Observing System polar platforms, for the late 1990’s. It employs eight CCD based discrete pushbroom cameras pointed at fixed angles, viewing forward and afterward along the spacecraft ground track. The sensors can work in two modes: Local and Global mode, with a ground resolution of 240m and 1.92km, respectively. Surface topography is to be derived on 720m grids, with better than 120m vertical accuracy [Diner et al., 1990].

The OPS instrument is already flying on-board the Japanese JERS-1 satellite, though no data was available by the time of completion of this thesis. This instrument has two cameras looking forwards and backwards along the ground track, with a ground resolution of 15m×27m. The OMI and the ASTER along track sensors are of higher resolution, e.g. the OMI and ASTER pixel resolutions will be 5m and 15m, respectively. These instruments will be described in more detail in section §2.8.
Chapter 2 Linear array imagery

The MEOSS imagery has been explored for thematic applications related to cartography, meteorology and geosciences. However, it also offered the first possibility of three dimensional photogrammetric reconstruction based on spaceborne three line imagery. With a ground resolution limited to 52m by 79m, simulated airborne MEOSS image data has been used for basic investigations and tests of photogrammetric compilation methods for threefold scanner data [Ebner et al., 1988]. The best results obtained gave estimated rms residuals of 308m in plan and 309m in height.

An airborne model of the MEOSS camera was flown giving data with similar resolution in the along and across track directions of 2m. The results obtained from orientating this data were presented by Ebner and Gill [1992] and showed an accuracy of 14.4m in three dimensions. These results were obtained by orientating the model with 4 GCPs and comparing the model with a DEM with an approximate accuracy of 2m in height.

Several authors have also studied the MOMS camera system, which has a 20m pixel resolution. Ebner et al. [1988] also tested MOMS simulated data and refer to different accuracies depending on the error of the orientation parameters. From these tests, an average residual of approximately 28m in three dimensions was found. The SPOT resection model developed by Gugan and Dowman [1988b] was also used in some tests with the MOMS-01 imagery. The results were inconclusive, due mainly to the low quality of the data, the small overlap of the stereopair used and the poor quality of the GCPs [Gugan and Dowman, 1987]. However, the study showed the possibility of orientating this type of imagery using an orbital model initially developed to orientate SPOT imagery.

Ebner and Müller [1987] developed a method specifically for the orientation of three line ALTI. They used a mathematical approach that may be interpreted as a special case of generalised combined point determination. It is able to orientate both frame photographs and imagery of digital line cameras [Hofmann and Müller, 1987]. The basic concept is that of reducing the strip photograph to an equivalent frame photograph having the same focal length and tilt [Case, 1967]. The orientation parameters of the line position of each point are calculated by interpolation within certain intervals [Hofmann and Müller, 1987]. The method is fully described in the next section.
2.7.3. Ebner-Müller's model

Ebner-Müller approach considers the parameters of exterior orientation varying from image to image, depending on the attitude of the platform [Ebner et al., 1988]. Due to the synchronization and the different perspectives produced by the sensors, a rigorous three dimensional reconstruction of the ground is possible. The model reconstruction is performed based on the collinearity equations for a bundle adjustment solution [equations 2.1]. The collinearity condition formulates the relationship between the image coordinates $x$, $y$, and the ground coordinates $X_p$, $Y_p$, $Z_p$ for each point $P$ and the unknown parameters for the exterior orientation $X$, $Y$, $Z$, $\omega$, $\varphi$, $k$ of each image [Fig 2.13].

\[
\begin{align*}
    x + v_x &= -f \cdot \frac{u_{11} (X_p - X_S) + u_{21} (Y_p - Y_S) + u_{31} (Z_p - Z_S)}{u_{13} (X_p - X_S) + u_{23} (Y_p - Y_S) + u_{33} (Z_p - Z_S)} \\
    y + v_y &= -f \cdot \frac{u_{12} (X_p - X_S) + u_{22} (Y_p - Y_S) + u_{32} (Z_p - Z_S)}{u_{13} (X_p - X_S) + u_{23} (Y_p - Y_S) + u_{33} (Z_p - Z_S)}
\end{align*}
\]

Fig 2.13 - Parameters of Ebner-Müller's model for along track imagery orientation.
where

\[ \begin{align*}
    x, y & \quad \text{are the image coordinates of point } P \text{ in image } I; \\
    v_x, v_y & \quad \text{are the residuals of } x, y; \\
    f & \quad \text{is the calibrated focal length of the camera;} \\
    X_S, Y_S, Z_S & \quad \text{are the unknown ground coordinates of the perspective} \\
    & \quad \text{centre of image } I; \\
    X_p, Y_p, Z_p & \quad \text{are the ground coordinates of point } P; \text{ and} \\
    u_{11}, \ldots, u_{33} & \quad \text{are the elements of the rotation matrix of image } I \text{ with the} \\
    & \quad \text{three rotation parameters } \omega, \varphi, k.
\end{align*} \]

As it is not possible to determine the parameters of exterior orientation for all images
\( I_j \), so-called orientation images \( I_k \) and \( I_{k+1} \) are introduced. The method consists in
finding the orientation parameters of the images \( I_k \) and \( I_{k+1} \), and representing those of
the images \( I_j, I_{j-1} \) and \( I_{j+1} \) as functions of the parameters of their neighbouring images.
This is done by means of interpolation as a function of time [Hofmann and Müller, 1987;
Ebner et al., 1988]. If linear functions are used to find the orientation parameters for
image \( I_j \), equation 2.2 is yielded.

\[
\begin{align*}
    X_1 &= \frac{d_{k+1} - d_j}{d_{k+1} - d_k} \cdot X_{I_k} + \frac{d_{k+1} - d_j}{d_{k+1} - d_k} \cdot X_{I_{k+1}} \\
    & \quad \vdots \\
    X_n &= \frac{d_{k+1} - d_i}{d_{k+1} - d_k} \cdot X_{I_k} + \frac{d_{k+1} - d_i}{d_{k+1} - d_k} \cdot X_{I_{k+1}}
\end{align*}
\]

where

\[ \begin{align*}
    X_1, \ldots, X_n & \quad \text{are the orientation parameters of image } I_j; \\
    X_{I_k}, \ldots, X_{I_{k+1}} & \quad \text{are the orientation parameters of image } I_k; \\
    d_j & \quad \text{is the read cycle number of orientation image } I_j; \text{ and} \\
    d_k, d_{k+1} & \quad \text{the read cycle numbers of orientation images } I_k, I_{k+1}.
\end{align*} \]

The image coordinates are considered as observations in a least-squares adjustment,
and are used together with additional control information [Ebner and Müller, 1986;
Ebner et al., 1988; Hofmann and Müller, 1987].
The distance between two neighbouring orientation images is very important for the compilation of three line imagery using this method [Hofmann and Müller, 1987]. This effect is significant for the results, since the exterior orientation of each line is calculated by the interpolation of parameters for the chosen orientation images. A further disadvantage of the Ebner-Müller method for along track stereoscopy is that it can only be applied to short flight-arcs, which consequently largely reduces its applicability. This is due to the elliptical shape of satellite orbits, which is not considered in the algorithm [Heipke and Kornus, 1991].

However, this model has the advantage of being adaptable for all types of LAI and for the orientation of frame photography [Ebner and Müller, 1987]. The projection equations for frame photography can be employed for performing analytical photogrammetric reductions such as resections, intersections and block triangulations [Case, 1967; Heipke and Kornus, 1991]. Two essential components of the software for three line scanner imagery are the digital image correlation, and the photogrammetric adjustment. The former is used to find conjugate points, and the latter is used to improve attitude and orbit data of the platform [Lehner and Gill, 1988]. Ebner-Müller’s model described above can also support SPOT imagery [Heipke and Kornus, 1991] as will be discussed in section §2.7.6.

2.7.4. Ebner-Müller’s model applied to MEOSS data

Ebner and Müller [1987] made some tests on MEOSS [Monocular Electro-Optical Stereo Scanner] simulated data, prior to the actual launch of the sensor. The results of these tests presented by Ebner et al. [1988] consisted of a preliminary test of the Ebner-Müller orientation model and an a priori evaluation of the MEOSS data. Although the ground resolution is limited to 52m by 79m, the MEOSS image data had sufficient resolution for basic investigations and tests of photogrammetric compilation methods for threefold stereo scanner data.

The results of orientating the MEOSS simulated imagery with Ebner-Müller orientation method were disappointing. The best models gave estimated rms residuals of 308m in plan and 309m in height, using 4 GCPs and additional positioning information. Improved results were obtained using more than one strip overlapping the same area. In
this case, estimated rms residuals of 50m in plan and 110m in height were obtained, with
the same control as in the single strip tests [Ebner et al., 1988].

Data acquired with the airborne model of the MEOSS camera were orientated by
Ebner and Gill [1992]. This camera was flown at 11,335m altitude, and the ground
resolution of the data in flight and across flight direction is similar, and equals 2m. The
rms residuals obtained in height from the comparison with a 2m accurate DEM were in
the order of 9.3m to 14.4m, for 99 GCPs and 4 GCPs used in the orientation process.
The model accuracy is very poor compared to the ground resolution of the data. These
results were obtained using matching techniques. However, the authors express their
belief towards a higher accuracy, 8m, based on the manual check of the model [Ebner
and Gill, 1992].

2.7.5. Ebner-Müller's model applied to MOMS data

A study was carried out with MOMS simulated data by Ebner et al. [1988], in order
to assess the accuracy properties of combined point determination within the MOMS-
02/D2 project. Recent work carried out by Ebner et al. [1992] with MOMS simulated
data with a ground resolution of 13.5m for the back and forwards looking cameras, and
of 4.5m for the nadir looking. An estimated accuracy of 13.6m in plan and of 12.2m in
height was obtained for a model orientated with 4 GCPs.

The poor results obtained are expected to be improved by the simultaneous
adjustment of two or more intersecting strips. The simulation study estimates a best
accuracy for a two strips data set with residuals of approximately 2m in plan and of 7m
in height [Ebner et al., 1992].

2.7.6. Ebner-Müller's model applied to SPOT data

In an independent trial, Heipke and Kornus [1991] orientated SPOT data using the
Ebner-Müller orientation model, and obtained promising results.

Two orientation images corresponding to the first and last image lines were
introduced, and the X, Y, Z coordinates of these orientation images were derived from
the SPOT header. Tie points were incorporated during the bundle adjustment process
and twenty four orientation parameters were considered for the two images. Additionally, equally distributed GCPs were used for the adjustment.

For a SPOT stereopair with a $B/H=0.4$, rms residuals of 46m and 16m were obtained in planimetry and in height, respectively, using 4 GCPs and 800 check points [Heipke and Kornus, 1991]. Other workers [Dowman et al., 1991] concluded that, in general, SPOT models are less accurate in planimetry than in height, agreeing with the results obtained by Heipke and Kornus [1991].

Minor systematic errors are still contained in the results. A linear interpolation of the orientation parameters is equivalent to a satellite movement in a straight line. However, since the SPOT satellite is moving in an elliptical orbit around the Earth, severe errors are encountered. A more sophisticated orbit orientation is expected to eliminate these and might also be able to improve the model [Heipke and Kornus, 1991].

2.8. Future along track satellite sensors

Several along track satellite sensors have been or are under study for launching in the late 1990s. In the study carried out for this thesis, the high resolution ASTER, OPS and OMI sensors were considered and are further described below. These systems were chosen because of advance studies, proposals and already existing literature. Furthermore, the OPS has already been launched in February 1992 [The Remote Sensing Society, 1992], although no data was delivered in time for inclusion on this thesis.

Other along track systems are under consideration. For example, future SPOT satellites are planned to carry a two-line camera with along track stereo capability [Heipke and Kornus, 1991]. The MISR is another along track sensor candidate for the first series of NASA Earth Observing System polar platforms. This sensor will employ eight CCD based discrete pushbroom cameras pointed at fixed angles, viewing forwards and afterwards along the spacecraft ground track, with a maximum ground resolution of 240m [Diner et al., 1990].
2.8.1. ASTER (Advanced Spaceborne Thermal Emission Radiometer)

The Japanese ASTER platform, will be carrying a 3 band optical sensor for Earth observation [Arai, 1991]. VNIR [Visible Near Infrared Radiometer] is a multispectral sensor covering visible and near infrared regions with a spatial resolution of 15m. The sensor will fly at an approximate altitude of 705 km imaging the Earth’s surface with a 5,000 element linear CCD sensor. This data is processed on-board, extracting 4,000 pixels from the full 5,000 pixels of imaged nadir and forwards looking data. The forward looking sensor is set to a viewing angle of 29.7°, which corresponds to a base to height ratio of approximately 0.6 [Arai, 1991].

2.8.2. OMI (Optical Mapping Instrument)

The OMI instrument was designed by British Aerospace (BAe), but no platform has yet been agreed. It was initially supposed to fly at an orbital altitude of approximately 824 km and orbital inclination of 98.7°. The baseline OMI design is for two views, one 20° forwards off nadir and the other 20° backwards. To enable a total coverage of the Earth’s surface in a minimum time, an across track capability of ±20° will be introduced. The base to height ratio (B/H) of the system is approximately 0.7. The sensor is composed of two 12,000 CCD linear arrays, with a 5m ground resolution [British Aerospace, 1991].

2.8.3. OPS (OPtical Sensor)

The OPS is an electronic scan type optical sensor installed on the JERS-1 System. The JERS-1 orbit is a sun synchronous orbit at a height approximately 568 km, with an orbital inclination of 97.7°. The sensor has a 4,096 CCD linear array with a 18.3 m range resolution, and 24.2 m resolution in the azimuth. The stereo capability is obtained by a nadir and 15.3° forwards imaging sensors, which corresponds to a base to height ratio of approximately 0.3 [MITI/NASDA, 1990].
2.8.4. Comparison between the ASTER, OMI and OPS systems

The pixel resolution and the base-to-height ratio of the imagery are the two main factors influencing the accuracy of the attainable three-dimensional information [Swann et al., 1987]. Taking this into account, it is expected to obtain models with better accuracies from the ASTER and OMI data. The OMI’s better pixel resolution and B/H may make it the sensor which will produce the best models. Conversely, given the above criteria, the OPS sensor is expected to give the poorest data.

<table>
<thead>
<tr>
<th>sensor</th>
<th>ASTER</th>
<th>OMI</th>
<th>OPS</th>
</tr>
</thead>
<tbody>
<tr>
<td>pixel resolution</td>
<td>15 m</td>
<td>5 m</td>
<td>18.3 x 24.2 m²</td>
</tr>
<tr>
<td>flying altitude</td>
<td>705 km</td>
<td>824 km</td>
<td>568 km</td>
</tr>
<tr>
<td>along track viewing angles</td>
<td>0° nadir</td>
<td>20° back</td>
<td>0° nadir</td>
</tr>
<tr>
<td></td>
<td>29.7° forw</td>
<td>20° forw</td>
<td>15.3° forw</td>
</tr>
<tr>
<td>B/H</td>
<td>0.6</td>
<td>0.7</td>
<td>0.3</td>
</tr>
</tbody>
</table>

Table 2.1 - Characteristics of the ASTER, the OMI and the OPS sensors.

2.9. Conclusions

The research previously performed and the models studied suggest that the following points must be considered when modelling LAI:

- The use of orbital parameters is the best approach to model the position of the satellite in space. It avoids the correlations between the orientation parameters and the observation equations, and gives a straight forward description of the platform’s movement with time [Green, 1985]. Polynomial approaches, such as the one adopted by
Ebner and Müller, can only be applied to short arcs of the orbit, introducing large errors into the final model [Heipke and Kornus, 1991].

- Ground control is necessary for an absolute orientation of the model. Although a reasonably good model can be obtained using only the on-board measured data, this however is insufficient to produce a good model. The ground control data orientates the three-dimensional model in space relative to the ground coordinate system with smaller residuals. A minimum of 6 control points is needed for an orientation without the need for further header data. A minimum of 2 GCPs is advisable for the absolute orientation of the zeroth order model obtained using the header data file.

- The header data should be used as it allows the orientation of a stereopair with a minimum of control points. The information given for the position and attitude of the sensor can be used advantageously to obtain a good initial approximation for the model [Hofmann and Müller, 1987; Gibson, 1986; Ackermann, 1986; O'Neill, 1991]. The absolute orientation may be improved using GCPs. From tests on the usefulness of the header data information, Gugan [1988] concludes that there is a small benefit when the attitude rates of change are incorporated. Westin [1990] states that further improvements can be achieved using just a few control points, and choosing appropriate orientation parameters, if the attitude data is used.

- Information derived from navigation systems is of interest [Hofmann and Müller, 1987; Gibson, 1986]. As Welch [1980] pointed out, errors introduced by variations in spacecraft attitude can be compensated for with the aid of on-board measurements. These usually occupy large volumes of data, which require appropriate methods of reducing the computational load of interpretation [Eales et al., 1987]. Hence, the use of polynomial models to describe the attitude variations with time is highly advantageous.

- The use of conjugate points and/or an additional bundle adjustment both contribute to improve the relative orientation of the model. This would support the reconstruction of the exterior orientation and strengthen the relative orientation of the model [Hofmann and Müller, 1987].

- The use of constraining equations, or weighting matrices, should be adopted to prevent large oscillations of the solution in the modelling process by keeping the values of the orbital and attitude parameters within the data specifications [Case, 1961; Veillet, 1991].
The use of a third image to the stereopair to secure a triple intersection of imaging rays, that can strengthen the geometric definition of the model, has been referred to by some authors [Welch, 1980; Kratky, 1989a]. Some linear array systems are already using this geometry, a third line array having been introduced to the imaging system [Lanzl, 1986].
Chapter 3.
Orientation model of linear array imagery

3.1. Main characteristics of the orientation model

The model presented in this chapter was primarily developed for the orientation of ALong Track Imagery (ALTI) from satellite platforms. However, in its latest version the algorithm is able to accept side looking imagery and is also able to orientate blocks of both along and across track linear imagery. The program was written in modules in order to process the various data types, and so that additional routines could easily be added to the suite. The main characteristics of the model were selected in view of the study carried out in chapter 2.

An orbital approach was adopted for the orientation algorithm, the orbital parameters having the advantage of having a low correlation and reducing the number of Ground Control Points (GCPs) required. Additionally, these parameters can be used for the orientation of long orbital arcs, since they take account of the elliptical shape of the satellite's orbit.

The use of \textit{a priori} information is a most important characteristic of the orientation model; this can be extracted from the header data file and/or from any other auxiliary file. Therefore, if available, on-board measurements of the satellite’s position and velocity may be used for an initial estimate of the orbital parameters. Attitude data is used to form a set of three sixth order polynomials that best describe the variation of roll, pitch and yaw with time respectively.
The ground and image coordinates of the control are introduced into the computation by means of an external file. If the information from the header is used to initially estimate the orientation parameters, the ground control and/or conjugate points are used for further refinement of the model. The model may eventually be orientated with very few GCPs. However, the orientation model may be poor, since it is highly dependent on the precision of *a priori* information. Generally, if no header data is used, a minimum of seven GCPs is advisable for the reconstruction of the stereomodel.

The images forming an along track stereopair are acquired during the same orbit. Hence, the orbital parameters used in the orientation process are set the same to all the images taken during that orbit. However, an additional orientation parameter must be adopted in the modelling process to describe the time delay due to the difference in the acquisition times of the images. As a result, the control required for the orientation of an along track stereopair is reduced to half that needed to orientate an across track stereopair. This will be further described in section §3.3.2. The introduction of the time displacement parameter to the orientation algorithm has some disadvantages. For example, it affects the line number for the origins of the extra images acquired during the same orbit. Consequently, a high correlation occurs between the time displacement parameter, the variations in pitch, and the effect of the terrain relief on the imagery. This aspect will be further explored in section §3.3.3.

Weight matrices are introduced to the algorithm to stabilise the solution and to keep the orientation parameters within the data specifications. These are defined using *a priori* estimated or known standard deviations for the parameters. This information may be extracted either from the header data, introduced by the user in accordance with the satellite specifications, or computed by the program itself. The use of weighing matrices during the orientation process is optional.

Information about the precision of the ground control is inserted into the computation through the control information file. The image coordinates of GCPs and conjugate points are automatically assigned to a quality factor class according to the precision of the measurements. This classification is used in the computation process as explained in section §3.2.7. The control information file has a pre-defined format that will allow the program to distinguish automatically between different types of control, orbit, image, and quality of the measurements.
3.2. The basic linear array imagery (LAI) orbital model

3.2.1. Coordinate systems adopted

The various coordinate systems used in the algorithm will next be introduced.

The Earth Centred Inertial Coordinate System (ECI) is the system to which the orbital parameters are referenced. It has its origin at the Earth’s centre of mass. The X axis points at the Vernal equinox, the Z axis points to the celestial north pole while the Y axis completes a right handed system with the other two [Fig 3.2].

The Local Orbital Reference System (LORS) is a moving coordinate system with its origin defined at the satellite’s centre of mass. The Z axis points in the same direction as the satellite position vector. The X axis is perpendicular to the Z axis and in the orbital plane pointing in the direction of the satellite motion, and the Y axis forms a right handed system with the other two axis.

The Attitude Measurement coordinate System (AMS) is fixed to the satellite’s body and is parallel to the local orbital reference system when the attitude angles are all zero.

The coordinates of the detectors are referred to the Sensor Coordinate System (SCS), whose origin is the perspective centre. The y axis is parallel to the array of detectors, pointing eastwards in the descending pass. The x axis points approximately in the direction of the satellite motion while the z axis forms a right handed system with the other two [Fig 3.1 and Fig 3.2]. The detector is one-dimensional, and the detector coordinates always have a zero x-coordinate. The z-coordinate is always constant, equivalent to minus the focal distance of the camera (-f). The measurement in the image will primarily result in the fractional line and sample number of the point image position. The fractional line number is then converted to time of observation.
Chapter 3 Orientation model of linear array imagery

![Image coordinate system.](image)

The Ground Control Point Reference System is the local system in which the ground control is given. The Geocentric Coordinate System was adopted for computations in this model to avoid discontinuities and cumulative errors in successive transformations of coordinates from more complex map projections. The geocentric coordinate system also strengthens the equations involved. The difference between this system and the ECI system is in the equatorial plane, between the Vernal Equinox and the Greenwich semi-meridian, given by the sidereal time. This offset is absorbed by the orbital parameters during the adjustment process [Westin, 1990].

As referred by Mather [1984], the usefulness of information depends upon which frame of reference the information is presented in. For this model, the computed coordinates of points identified in the imagery can be output either in the Geocentric Coordinate System, Geographical Coordinate System or in Universal Transverse Mercator. Further information on the characteristics of these systems of coordinates may be obtained from Snyder [Snyder, 1987].

3.2.2. The Eulerian orbital parameters

Once its Eulerian parameters are known, a satellite’s orbit is well defined [Green, 1985]. These parameters define the position of the satellite relative to the ECI system of coordinates as shown in Fig 3.2.
Chapter 3 Orientation model of linear array imagery

Fig 3.2 - Eulerian parameters of a satellite orbit.

where

- \( a \) is the semi-major axis of the orbit;
- \( i \) is the inclination of the orbit;
- \( \Omega \) is the right ascension of ascending node;
- \( F \) is the true anomaly of the satellite’s position for a given time;
- \( w \) is the argument of the perigee;
- \( e \) is the eccentricity of the orbit (not represented in fig 3.2); and
- \( OXYZ \) is the ECI coordinate system.

3.2.3. Modelling the satellite’s course along the orbit

The orientation parameters defining a satellite’s orbit are continually changing, though they change in a predictable way. The satellite moves along a well defined orbit.
Chapter 3 Orientation model of linear array imagery

path which may be easily modelled by the Eulerian parameters and their change with time [Gugan, 1987].

The Eulerian parameters describe the position of a satellite on its orbit for any given time. Once these orbital parameters are known, the movement of the satellite along the orbital plane is described by equations [3.1] to [3.3] [Green, 1985]:

\[
\Omega' = \frac{3}{2} \frac{J_2 \cdot n \cdot R_e^2}{a^2 \cdot (1-e^2)^{3/2}} \cdot \cos(i) - \nu
\]  

\[3.1\]

\[
w' = -\frac{3}{4} \frac{J_2 \cdot n \cdot R_e^2}{a^2 \cdot (1-e^2)^{3/2}} \cdot [1-5\cos^2(i)]
\]  

\[3.2\]

\[
M' = \frac{3}{4} \frac{J_2 \cdot n \cdot R_e^2}{a^2 \cdot (1-e^2)^{3/2}} \cdot [3\cos^2(i) - 1] + n
\]  

\[3.3\]

where the mean motion, \( n \), can be computed using equation [3.4]

\[
n^2 a^3 = \mu
\]  

\[3.4\]

where:

\[
\mu = G m_e = 3.986005 \times 10^{14} \text{ m}^3/\text{sec}^2
\]

\( J_2 = 0.001082 \) is the dominant term of the Earth’s gravitational potential;

\( \Omega' \) is the rate of change with time of the right ascension;

\( w' \) is the rate of change with time of the argument of the perigee;

\( E \) is the eccentric anomaly;

\( M \) is the mean anomaly;

\( M' \) is the rate of change with time of the mean anomaly;

\( G \) is the Universal Gravitational Constant;

\( \nu \) is the Earth angular velocity;

\( e \) is the eccentricity of the orbit;

\( m_e \) is the Earth’s mass; and

\( R_e \) is the Earth’s equatorial radius.
Using the expression in equation [3.5]:

\[ M = E - e \cdot \sin E \]  \[\text{[3.5]}\]

the variation of the eccentric anomaly with time is given by equation [3.6].

\[ E' = \frac{M'}{1 - e \cos E} \]  \[\text{[3.6]}\]

If the relation between the eccentric anomaly and the true anomaly given in [3.7] is used, the variation of the true anomaly with time may be calculated as in equation [3.8].

\[ \tan \left(\frac{F}{2}\right) = \sqrt{\frac{1+e}{1-e} \tan \left(\frac{E}{2}\right)} \]  \[\text{[3.7]}\]

\[ F' = \sqrt{\frac{1+e}{1-e} \cos^2 \left(\frac{F}{2}\right)} \cdot E' \]  \[\text{[3.8]}\]

The effect of the Earth's rotation, \( v \), is added directly to the effect of \( \Omega' \) since \( v \) and \( \Omega' \) are angular velocities about the same axis OZ. Due to the small eccentricity, \( e \), of this type of satellite, the other Eulerian parameters suffer small variations with time. Such variations are negligible for orientation purposes.

### 3.2.4. Additional attitude parameters

The satellite is not perfectly pointing towards the centre of the Earth; hence the Attitude Measurement System (AMS) differs from the Local Orbital Reference System by the three angles roll, pitch and yaw [§2.3.2]. These time dependent angles describe the attitude of the satellite. It is necessary to model their variation with time to know the attitude in any specific point of the satellite's orbit. The variation can be modelled by the three sets of polynomials given by equations [3.9].

\[
\begin{align*}
\omega &= \omega_0 + f_\omega(x) \\
\varphi &= \varphi_0 + f_\varphi(x) \\
k &= k_0 + f_k(x)
\end{align*}
\]  \[\text{[3.9]}\]
where \( f_{\omega}(x), f_{\varphi}(x) \) and \( f_{k}(x) \), represent respectively the roll, pitch and yaw as polynomial functions of \( x \), and where \( x \) is a measure of time. The values of \( \omega_o, \varphi_0, \) and \( k_0 \) correspond to roll, pitch and yaw respectively for the first line of the image.

3.2.5. Sensor to geocentric coordinates transformation

A set of orthogonal matrices is used to describe the transformations from the sensor to the ground coordinate systems. The sensor-body transformation relates the sensor coordinate system to the attitude reference system, and accounts for the sensor look angle. This transformation is constant within images of the same strip, and may be represented by the rotation matrix \( R_m \) given in (3.10):

\[
R_m = R_{\beta} \cdot R_{\alpha} = \begin{bmatrix}
\cos \alpha & 0 & -\sin \alpha \\
\sin \alpha \sin \beta & \cos \beta \cos \alpha & \sin \alpha \cos \beta \\
\sin \alpha \cos \beta & -\sin \beta \cos \alpha & \cos \alpha \cos \beta
\end{bmatrix}
\]

where \( \alpha \) represents the angle along the flight direction and \( \beta \) the across track angle. The angle \( \beta \) is defined as for SPOT [CNES, 1989] and is assumed positive for the left image and negative for the right image. The angle \( \alpha \) is positive for a forwards looking image and negative otherwise.

The body-flight transformation relates the attitude reference system to the orbital reference system, thus accounting for the attitude deviations from the local reference system. It is a function of time within one scene, and it may be represented by the rotation matrix \( R_A \) as in equation (3.11):

\[
R_A = R_{k} R_{\varphi} R_{\omega} = \begin{bmatrix}
\cos \kappa \cos \varphi & \cos \kappa \sin \varphi \sin \omega & -\cos \kappa \sin \varphi \cos \omega \\
\sin \kappa \cos \varphi & +\sin \kappa \cos \omega & +\sin \kappa \sin \omega \\
-\sin \kappa \cos \varphi & -\sin \kappa \sin \varphi \sin \omega & \sin \kappa \sin \varphi \cos \omega
\end{bmatrix}
\]

\[
R_{k} R_{\varphi} R_{\omega} = \begin{bmatrix}
\cos \varphi & \cos \varphi \sin \omega & -\cos \varphi \sin \omega \\
-\sin \varphi & +\sin \varphi \cos \omega & +\sin \varphi \sin \omega \\
\sin \varphi & -\cos \varphi \sin \omega & \cos \varphi \cos \omega
\end{bmatrix}
\]
The flight-inertial transformation relates the orbital reference system to the ECI Coordinate System. This transformation is a function of the orbital parameters, and thus is a function of time, which can be defined by the product of matrices $R_0 = R_{F+w} \cdot R_i \cdot R_\Omega$ resulting in the rotation matrix given by equation [3.12].

$$R_0 = \begin{bmatrix}
-sin \Omega \cos i \cos (F+w) & sin \Omega \sin i & -sin \Omega \cos i \sin (F+w) \\
-cos \Omega \sin (F+w) & cos \Omega \cos (F+w) & sin \Omega \cos (F+w) \\
sin \Omega \sin (F+w) & -cos \Omega \cos i \sin (F+w) & cos \Omega \cos i \sin (F+w) \\

cos i \cos (F+w) & sin i \sin (F+w) & sin i \sin (F+w)
\end{bmatrix}$$  

[3.12]

The differences between the ECI system and the Geocentric Coordinate System, adopted as a ground control reference system, are taken into account during the orientation process. These consist of shifts between the two systems [Westin, 1990].

The transformations presented above may be used to describe the relationship between the image coordinates of one point and its geocentric coordinates. The rotation matrix $R$ used to transform from sensor to geocentric coordinates is obtained by considering the effect of all the orientation parameters as in equation [3.13].

$$R = R_0 \cdot R_A \cdot R_m$$  

[3.13]

Simultaneously, the position of the satellite can be computed using equation [3.14].

$$\begin{bmatrix}
X_s \\
Y_s \\
Z_s
\end{bmatrix} = R_0^T \cdot \begin{bmatrix} 0 \\
r \end{bmatrix}$$  

[3.14]

where $r$ is defined by equation [3.15].

$$r = \frac{a \cdot (1 - e^2)}{1 + e \cdot \cos F}$$  

[3.15]

Hence, the relationship between image and ground coordinates for each image can be described by equation [3.16]:

$$\begin{bmatrix}
X_A \\
Y_A \\
Z_A
\end{bmatrix} = \begin{bmatrix}
X_s \\
Y_s \\
Z_s
\end{bmatrix} + s \cdot R \cdot \begin{bmatrix} 0 \\
y \\
-f
\end{bmatrix}$$  

[3.16]
where \([X_A, Y_A, Z_A]^T\) are the geocentric coordinates of the ground control point, 
\([X_s, Y_s, Z_s]^T\) are the geocentric coordinates of the satellite at the time of acquisition, and 
\([0, y, -f]^T\) are the image coordinates of the control point.

The origins of the AMS and of the SCS differ by the difference of the positions of the 
centre of mass of the satellite and the sensor's perspective centre. This is not introduced 
specifically into the computations for two main reasons. First, such difference is very 
small when compared to the geocentric distance of the satellite, and to the altitude of the 
satellite above the Earth's surface. Second, if this small translation becomes important to 
the model orientation, the orientation parameters will be adjusted to account for this 
small deviation. This is possible, since the relative position of the sensor's perspective 
centre relative to the AMS will not vary much during the time of acquisition of one 
image.

3.2.6. Observation equations

Each GCP is identified in at least one image from which five observations result: two 
image coordinates and three ground coordinates. The two image coordinates are the line 
and sample numbers of the point, while the ground coordinates are its geocentric 
coordinates. The line number is used in the orientation process as the time variable to 
define the satellite's position in the orbit.

The image and geocentric coordinates of control points are used to form observation 
equations, and to improve the initial values of the orientation parameters. Each control 
point identified on each image will form the set of equations [3.17]:

\[
\begin{bmatrix}
0 \\
y \\
-f
\end{bmatrix}
= \frac{1}{s} \cdot U 
\begin{bmatrix}
X_A - X_s \\
Y_A - Y_s \\
Z_A - Z_s
\end{bmatrix}
\]

where matrix \(U\) is given by equation [3.18]:

\[
U = [R_A, R_0, R_m]^T
\]

From equations [3.17], the two collinearity equations given by equation [3.19] are 
derived.
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\[ \begin{align*}
F_x &= -f \cdot \left( u_{11} (X_A - X_S) + u_{12} (Y_A - Y_S) + u_{13} (Z_A - Z_S) \right) \\
F_y &= y - f \cdot \left( u_{21} (X_A - X_S) + u_{22} (Y_A - Y_S) + u_{23} (Z_A - Z_S) \right)
\end{align*} \]

[3.19]

For an ideal situation, the values of \( F_x \) and \( F_y \) would be zero thus giving observation equations. This does not occur in practice, and consequently the residuals of the observation equations of \( n \) control points, identified on the imagery, form matrix \( F \) (equation [3.20]):

\[ F = \begin{bmatrix} F_1 \\ \vdots \\ F_i \\ \vdots \\ F_n \end{bmatrix} = 0 \]

[3.20]

where the various components \( F_i \) are given by equation [3.21].

\[ F_i = \begin{bmatrix} F_x \\ F_y \end{bmatrix} \]

[3.21]

These \( F_x \) and \( F_y \) are defined by equations [3.19]. Hence, for the \( n \) control points identified in the imagery, there are \( 2n \) observation equations, which correspond to \( n \) pairs of observation equations.

3.2.7. The orientation process

The unknowns in the observation equations [3.20] are the orientation parameters; i.e., the Eulerian orbital parameters plus the attitude parameters. A number of control points exceeding half the number of orientation parameters being considered are required to compute a solution with some redundancy. The formulation of the problem to solve is then straightforward and can be described in matrix form by equation [3.22] [Mikhail, 1976].

\[ A \cdot v + B \cdot \Delta = F \]

[3.22]

where
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A is a matrix describing the effect of small changes in the measurements; 
\( v \) is the vector of the estimated errors of the measurements; 
B is a matrix describing the effect of small variations of the orientation parameters; 
\( \Delta \) is the correction vector of the parameters considered; and 
F is the vector of residuals of the observation equations.

The additional effect of small changes in the image and ground coordinates of the control points may be introduced into the formulation [Mikhail, 1976]. If the standard deviations, or the quality factors of the coordinates are given, these may be advantageously introduced to the orientation process. A diagonal matrix, \( Q_i \), containing the inverse of the squares of \textit{a priori} standard deviations of the observations will retain that information. This matrix may be expressed by equation [3.23], assuming a theoretical independence between the various measurements.

\[
Q_i = \sigma_0^2 \begin{bmatrix}
1/\sigma_x^2 & 0 & 0 & 0 & 0 \\
0 & 1/\sigma_y^2 & 0 & 0 & 0 \\
0 & 0 & 1/\sigma_{x_A}^2 & 0 & 0 \\
0 & 0 & 0 & 1/\sigma_{y_A}^2 & 0 \\
0 & 0 & 0 & 0 & 1/\sigma_{z_A}^2 \\
\end{bmatrix}
\]  

[3.23]

Matrix Q contains all the information on every point under consideration in the orientation process in equation [3.24]:

\[
Q = \begin{bmatrix}
Q_i & 0 & 0 & 0 & 0 \\
0 & \ldots & 0 & \ldots & 0 \\
0 & 0 & Q_i & 0 & 0 \\
0 & \ldots & 0 & \ldots & 0 \\
0 & 0 & 0 & 0 & Q_n \\
\end{bmatrix}
\]  

[3.24]

An additional matrix, \( A_i \), describing the effect of small changes in the measurements on the observation equations is computed for each observation (equation [3.25]).
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\[ A_i = \begin{bmatrix} \frac{\partial F_x}{\partial x} & \frac{\partial F_x}{\partial y} & \frac{\partial F_x}{\partial X_A} & \frac{\partial F_x}{\partial Y_A} & \frac{\partial F_x}{\partial Z_A} \\ \frac{\partial F_y}{\partial x} & \frac{\partial F_y}{\partial y} & \frac{\partial F_y}{\partial X_A} & \frac{\partial F_y}{\partial Y_A} & \frac{\partial F_y}{\partial Z_A} \end{bmatrix} \]  

[3.25]

Matrix A contains all the information on the observation equations with the following form:

\[ A = \begin{bmatrix} A_1 & 0 & 0 & 0 & 0 \\ 0 & 0 & A_i & 0 & 0 \\ 0 & 0 & 0 & A_i & 0 \\ 0 & 0 & 0 & 0 & A_n \end{bmatrix} \]  

[3.26]

where \( n \) is the number of control points identified in the image. Matrix B contains the rates of change of the solution due to small variations of the orientation parameters and has the form shown by equation [3.27].

\[ B = \begin{bmatrix} B_1 \\ \vdots \\ B_i \\ \vdots \\ B_n \end{bmatrix} \]  

[3.27]

where \( B_i \) is given in equation [3.28].

\[ B_i = \begin{bmatrix} \frac{\partial F_x}{\partial i} & \frac{\partial F_x}{\partial a} & \frac{\partial F_x}{\partial \Omega} & \frac{\partial F_x}{\partial \phi} & \frac{\partial F_x}{\partial \omega} & \frac{\partial F_x}{\partial \kappa} & \frac{\partial F_x}{\partial i'} & \frac{\partial F_x}{\partial a'} & \frac{\partial F_x}{\partial \Omega'} & \frac{\partial F_x}{\partial \phi'} & \frac{\partial F_x}{\partial \omega'} & \frac{\partial F_x}{\partial \kappa'} \end{bmatrix} \]  

[3.28]

Due to the non-linearity of the observation equations, a numerical method is adopted to describe the partial derivatives of the functions, \( F_i \), relative to the orientation parameters. Once all the matrices are computed, an iterative process is used to solve for the orientation parameters that best adjust to the observations. If free adjustment is desired, the correction vector for the \( i \)th iteration is simply computed by the method of adjustment of indirect observations. In this case, the correction vector is given by the equation [3.29]:

\[ \Delta_i = [B^T \cdot (A \cdot Q \cdot A^T)^{-1} \cdot B]^{-1} \cdot B^T \cdot (A \cdot Q \cdot A^T)^{-1} \cdot F \]  

[3.29]
After convergence, the residuals of the measurements are computed using equation [3.30].

\[ v = Q . A^T . ( A . Q . A^T )^{-1} . ( F - B . \Delta ) \]  

[3.30]

3.2.8. The constrained solution

Constraints are usually adopted to enforce the camera, or points in the object space, to conform to some functional or geometrical relationship or to lie within certain bounds defined by weighting. These constraints may make use of the geometrical properties of the physical situation and/or weighting factors to reduce the magnitude of error propagation particularly in areas of lacking in ground control. The weight constraint assigns weights to every parameter in the projection equations, corresponding to either the accuracy of the original observations or some approximations of these accuracies. This ensures that errors will not propagate through the iterative process [Case, 1961].

If \textit{a priori} information about the satellite parameters is known, and if this information is considered reliable, it may be desirable to weight the parameters rather than to permit free adjustment. This technique uses the unified approach to least-squares adjustment described by Mikhail [1976], in which case the corrections to the estimates of the orientation parameters are computed according to equation [3.31]:


[3.31]

where \( F_{xx} \) is the vector sum of the correction vectors of the previous \( i-i \) iterations, and \( W_{xx} \) is the weight matrix based on the inverse square of the standard deviations of the parameters. The weight matrix may also be adjusted to the type of data or LAI to orientate. This will be studied in chapter 6. The final residuals are still computed using equation [3.30].

Westin [1990] verified that large oscillations sometimes occur during the iterative process even when constraints are adopted. To solve this problem, Westin proposed the use of an additional set of fictitious equations of unknown parameters to stabilise the system. The condition equations are thus reformulated for the first iteration as in equation [3.32].
It is claimed that this formulation prevents the solution from suffer large variations during the first iteration, and subsequent propagation of those variations in the successive iterations.

### 3.2.9. Control requirements

The number of GCPs required for the orientation of the model depends on the number of orientation parameters considered. It is common to use the four orbital parameters a, i, \( \Omega \), and \( \Phi \), the three attitude parameters (roll, pitch, and yaw) corresponding to line zero, and their linear rates of change with time. Such a model makes use of 10 orientation parameters.

Each ground control gives two observation equations if the 3 ground coordinates and the 2 image coordinates of the point are known. Hence, theoretically, a solution is possible if at least 5 GCPs are used per image. A minimum of 6 GCPs is required for a solution with some redundancy.

Tests carried out with SPOT data showed that sometimes even 6 GCPs may not be sufficient. Sometimes, the solution is not stable and more ground control is needed [Neto and Dowman, 1991].

### 3.3. Along track imagery model refinement

#### 3.3.1. The time displacement parameter

The modelling process described in the previous sections considered an independent orientation of the two, or more, linear array images forming the stereomodel. Hence, the algorithm must be run separately for each of the images under consideration, taking a lot of CPU time. Additionally, six GCPs need to be identified per image to obtain a model...
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as described in §3.2.9. However, an along track stereo model is formed with images acquired during the same orbit pass, and this characteristic may be used to simplify the orientation model and reduce the number of control points needed.

Concerning discontinuous SPOT scenes taken during the same satellite pass, Westin [1990] refers to the feasibility of their simultaneous orientation by connecting them into one long image by pass-processing techniques, thus reducing the need for geodetic control. A similar procedure may be adopted for the orientation of ALTI. The orbital parameters of images taken during the same satellite pass may be considered common to the images, and the time variant parameters may be related to the parameters of the first image by means of an additional parameter. The time displacement parameter, \( \Delta t \), describing the time between the first lines of each image may be used for that purpose as shown in Fig 3.2a and Fig 3.3b.

![Diagram](image1)

**Fig 3.3a** - Time displacement \( \Delta t \) between two images taken during the same orbit [represented on the image].

![Diagram](image2)

**Fig 3.3b** - Time displacement \( \Delta t \) between two images taken during the same orbit [orbit representation].
This configuration makes use of the orbital parameters plus the attitude parameters to orientate the sensor in space. The time displacement parameter, \( \Delta t \), is used to fix the position of the \( i^{th} \) image relative to the first image. Thus, the orientation parameters common to the images are the semi-major axis of the orbit, the inclination, and the longitude of the ascending node. The other orientation parameters are given to the first line of the first image. They are computed for each image by considering the time difference, \( \Delta t \), as a difference in line numbers between the images.

Any time dependent parameter, \( p_i \), is described by a certain value, \( p_0 \), corresponding to the first line of the first image, and \( p_v(x) \), the change with time. If conjugate points have line number \( x_1 \) in the first image, and \( x_2 \) in the second image, the time dependent parameters computed for the first image are given by equation [3.33],

\[
p_i = p_0 + p_v(x_1)
\]  \hspace{1cm} [3.33]

and for the second image by equation [3.34].

\[
p_i = p_0 + p_v(\Delta t + x_2)
\]  \hspace{1cm} [3.34]

If \( \Delta t \) is introduced as an additional parameter, then in \( B_i \) a further partial derivative is introduced as seen in equation 3.35. This extra derivative is zero for the first image of any particular pair of images, or set of images.

\[
B_i = \begin{bmatrix}
\frac{\partial F_x}{\partial t} & \frac{\partial F_x}{\partial a} & \frac{\partial F_x}{\partial \Omega} & \frac{\partial F_x}{\partial \Omega} & \frac{\partial F_x}{\partial \phi} & \frac{\partial F_x}{\partial \omega} & \frac{\partial F_x}{\partial \kappa} & \frac{\partial F_x}{\partial \kappa} & \frac{\partial F_x}{\partial \Delta t} \\
\frac{\partial F_y}{\partial t} & \frac{\partial F_y}{\partial a} & \frac{\partial F_y}{\partial \Omega} & \frac{\partial F_y}{\partial \Omega} & \frac{\partial F_y}{\partial \phi} & \frac{\partial F_y}{\partial \omega} & \frac{\partial F_y}{\partial \kappa} & \frac{\partial F_y}{\partial \kappa} & \frac{\partial F_y}{\partial \Delta t}
\end{bmatrix}
\]  \hspace{1cm} [3.35]

3.3.2. Along track stereo model control requirements

A major advantage of the use of \( \Delta t \) in the model orientation is the reduction of control requirements. For a typical \( 10+n_f \) parameters solution, a minimum of \( 6+n_t/2 \) GCPs is required for a solution with some redundancy, where \( n_t \) is the number of time displacement parameters being used in the orientation process. There is only one time displacement parameter per each extra image acquired during the same orbit path. Hence, \( n_t \) equals the number of images minus one, corresponding to the first image taken
for time reference. Theoretically, the way these control points are distributed in the scene is not of importance. The only requirement is that one control point is identified on each image.

If no header data is used to form an initial orientation, the control needed for the orientation of an along track stereopair will be half of that needed to orientate an across track stereopair. To orientate a SPOT stereopair, six control points are required per left and right image. The orientation of an along track stereopair is possible with six control points identified on any of the images, forwards, backwards or nadir looking. The only requirement is that one ground control must be identified on each of them. The remaining control points may be measured on any image of the stereopair.

3.3.3. Correlations between the orientation parameters

The time displacement is used to describe the difference in line numbers between the images taken during the same orbit segment. The line numbers are also used as a measure of time, and so, $\Delta t$ is highly correlated to some of the orientation parameters. Several problems may arise from its insertion in the iteration process.

It was previously described in section §2.4.2 how the line number of a control point is affected by the terrain relief for ALTI geometry. The extraction of the height information is thus dependent on the difference in line numbers for each image point, since the parallax is characterized by the difference in line number as well. Therefore, the height extraction is highly correlated to the value of $\Delta t$. Additionally, variations in pitch also have an effect in the line number of the imaged points [Fig 2.2]. Therefore, the variations in pitch and the time displacement affect the model in the same way, and thus are highly correlated. Weights may be adopted to constrain the effect of these correlations during solution.

In across track geometry, extraction of height information is directly related to the roll. Although there is not a high correlation between the orientation parameters, it has been shown for SPOT that roll has the highest variation of all the attitude parameters [Westin, 1991a]. Hence, constraining this parameter to the satellite specifications is theoretically advantageous too.
The errors introduced by the possible misinterpretation of the GCPs on the imagery are accounted for by matrix Q, which contains the information about the quality of the measurements. This information interacts with that given by the matrix of weighting of the orientation parameters, helping in the constraining process.

The constraints may be introduced to the computation through the weight matrix or, if not enough, by restraining the simultaneous calculation of these orientation parameters.

The weight matrix can be built based on the inverse square of \textit{a priori} standard deviations of the orientation parameters. Hence, the weights given to the parameters will depend on the standard deviations initially assigned to those parameters. These can be chosen to give more weight to certain parameters to the detriment of the remaining. This method assumes the independency of the orientation parameters.

Another method which has been suggested is to base the weight matrix on the co-variance matrix. This matrix can be obtained during the iterative process. However, algebraic correlations occur and the method is not theoretically correct, as further stated in chapter 7.

3.3.4. Restrictions using the time displacement parameter

As previously described, there is a high correlation between the time displacement parameter, the pitch and the precision of the measurement of the line numbers. This has a strong effect on the precision to which the height is extracted. The initial estimate of the time displacement parameter is thus very important. Reliable initial data for the other orientation parameters also strengthens the information contained in the weight matrix \( W_{xx} \), thus strongly controlling possible oscillations during the iterative process. This factor may determine the effectiveness of the convergence or not of the algorithm.

When convergence is not achieved due to big oscillations of \( \Delta t \) during the iterative process, another method may be adopted. The time displacement parameter is kept constant during the first iteration and it is only considered in the orientation process from the second iteration onwards. However, this implies that a reliable initial value must be known for \( \Delta t \). The accuracy of the initial value of \( \Delta t \) that will ensure the convergence of the algorithm will be studied in chapter 6.
3.4. Initial estimation of the orientation parameters

The precision of the values initially assigned to the orientation parameters is highly dependent on the type of information from where they are extracted. Whenever available, the header data should be used as it gives the best initial data. However, sometimes this data may not be available and alternative methods must be readily available.

3.4.1. The header, the auxiliary and the control data files

The header data gives information on the inertial position and velocity of the platform for several points along the orbit. This information may be used to estimate the initial values of the Eulerian parameters [§3.4.2]. It also gives information on the attitude changes over time, as well as information on the time of acquisition of the imagery. The variation with time of roll, pitch and yaw may be used to form a set of attitude models for the area under consideration in the orbit, while the time of acquisition of the scene may be used for the initial estimate of $\Delta t$.

If no header data is available, an auxiliary data file with information given by the user must give sufficient information about the orbit to estimate the most important orientation parameters. Examples of auxiliary data files are presented in Appendix A.

Ground and image coordinates are both required for the absolute orientation of the model. This is introduced to the program suite through the control data file, where information about the strip and image corresponding to the measurements for each point is specified [Appendix A]. To form matrix $Q$ [§3.2.7], additional information must be given describing the data quality. Matrix $Q$ is used to weight the control information according to its accuracy, and adds information on the difficulties found by the user during the point identification process. The quality factor classification adopted will be assessed in chapter 4.
3.4.2. Initial estimation of the orbital parameters

The on-board measured positions and velocities of the satellite along the orbit path given in the header data may be used to estimate the orbital parameters using equations [3.37] to [3.44]. The position of the satellite is given in the header data in the Earth Centered Inertial Coordinate System, in [X, Y, Z]. The velocity of the satellite is also given in the same coordinate system by [Vx, VY, VZ]. Both the position and velocity of the satellite are measured for several line numbers during image acquisition. For SPOT, the position and velocity of the satellite is given every minute. Hence, the position and velocity of the satellite have to be estimated by interpolation for the first line of the image under consideration.

Defining \( r = [X, Y, Z]^T \) the position of the satellite in orbit, and \( v = [Vx, VY, VZ]^T \) the velocity of the satellite at that same position, the orbital parameters may be estimated using the formulae described by Green [1985].

The semi-major axis, \( a \), of the orbit is given in equation [3.37]

\[
a = \frac{\mu \cdot |r|}{2 \mu - |r| \cdot |v|^2}
\]  

where \( \mu = G \cdot m_e \) as in §3.2.3.

The vector angular momentum, \( h \), per unit reduced mass is obtained in equation [3.38]

\[
h = \begin{bmatrix} h_1 \\ h_2 \\ h_3 \end{bmatrix} = r \times v = \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \times \begin{bmatrix} Vx \\ VY \\ VZ \end{bmatrix}
\]

which is used to estimate the right ascension of the ascending node, \( \Omega \), the orbit inclination, \( i \), the eccentricity, \( e \) and the eccentric anomaly, \( E \) (equations [3.39] to [3.42]).
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\[ \Omega = - \arctan \frac{h_1}{h_2} \]  

\[ i = \arccos \frac{h_3}{|h_1|} \]  

\[ e = \sqrt{1 - \frac{|h_2|^2}{\mu \cdot a}} \]  

\[ E = \pm \arccos \frac{a - |r|}{a \cdot e} \]

The plus sign in the expression for the eccentric anomaly, \( E \), corresponds to the satellite's outward journey, from perigee to apogee, when its radial velocity is positive. The sign of the radial velocity is that of the scalar product \( r \cdot v \). Additionally, the true anomaly, \( F \), is given by equation [3.43]

\[ F = 2 \arctan \left[ \frac{\sqrt{1 + e} \cdot \tan (E/2)}{1 - e} \right] \]  

and the argument of perigee by equation [3.44]

\[ w = \pm \arccos \left( \frac{X \cos \Omega + Y \sin \Omega}{|r|} \right) \cdot F \]  

where the plus sign corresponds to positive \( Z \).

However, if no header data is available, the orientation parameters have to be estimated based on other types of information. The auxiliary data file is used for this purpose. The orbit eccentricity is usually known and may be given by the user. Approximate values of the altitude of the platform and of the orbit inclination are also
known. These may be introduced to the program through the auxiliary data file. This
data is then used to estimate the true anomaly and the right ascension of the ascending
node of the orbit using the equations later derived.

First, the azimuth of the orbital plane is calculated for the average position of the
ground control using equation [3.45]. The value obtained is then used to estimate the
corrections to add to the latitude and longitude of the first ground control on the first
image of the strip. This procedure shifts the satellite to the orbital plane, and is given by
equations [3.45] to [3.48].

\[
A = \frac{\pi}{2} - \arcsin \left( \frac{\cos (\pi-i)}{\cos (\varphi)} \right) \quad [3.45]
\]

\[
\Delta \lambda = \frac{a - R_e}{R_e} \tan (\beta) \cdot \sin (A) \quad [3.46]
\]

\[
\Delta \varphi = - \frac{a - R_e}{R_e} \tan (\beta) \cdot \cos (A) \quad [3.47]
\]

where
- \( i \) is the inclination of the orbital plane;
- \( \varphi \) is the latitude of the first control point;
- \( \lambda \) is the longitude of the first control point;
- \( \Delta \varphi \) is the correction to apply to the latitude \( \varphi \);
- \( \Delta \lambda \) is the correction to apply to the longitude \( \lambda \);
- \( \beta \) is the across track angle;
- \( R_e \) is the Earth radius;
- \( a \) is the semi-major axis of the orbit; and
- \( A \) is the azimuth of the orbital plane.

\[
\begin{align*}
\lambda_s &= \lambda + \Delta \lambda \\
\varphi_s &= \varphi + \Delta \varphi
\end{align*} \quad [3.48]
\]

The true anomaly and the right ascension to be used in the first iteration are finally
obtained using equations [3.49] and [3.50].
Later, an extra correction for the effect of the along track angle is applied. For this purpose, the line number \( x \) of the first GCP is used. The true anomaly used during the first iteration is given by equation [3.51]:

\[
F = F_{init} - \left[ \frac{h}{r} \tan(\alpha) \cdot \text{pix} + x \right] \cdot F' \tag{3.51}
\]

where

- \( h \) is the satellite's approximate altitude;
- \( r \) is the satellite's distance to the centre of the Earth;
- \( \text{pix} \) is the CCD dimension;
- \( \alpha \) is the along track angle;
- \( x \) is the line of the first control point on the first image; and
- \( F' \) is the rate of change of the true anomaly.

3.4.3. Computation of the attitude model

The header data file provides on-board measurements of the roll, pitch and yaw over the time of image acquisition. This allows a mathematical model to be built up describing the attitude variation as a function of time. The procedure chosen for this purpose was a least squares adjustment of a set of three sixth order polynomials, one equation per attitude angle. Sixth order polynomials were adopted after some tests were performed on attitude information from SPOT headers and attitude data simulated using Westin's variograms.

Westin [1991a] derived attitude variograms from SPOT headers data, for data strips as long as 60 seconds. Plots of these variograms are presented by Westin [1991a], which were considered for the studies involving attitude data. Examples of some attitude data derived from using those variograms are shown in figure 3.4 for roll, pitch and yaw, for a time span of approximately 150 seconds.
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The tests were carried out on a Micro VAX II / GPX workstation at the Department of Photogrammetry and Surveying (P&S), University College London (UCL). A polynomial approach was adopted in preference to variogram functions since they involve less complex calculations and the orientation model becomes less time consuming.

Four continuous SPOT headers obtained from the SPOT OEEPE test were used for tests on real attitude data [Dowman et al., 1991]. This attitude data covered an area approximately 240km long, taken over about 36 seconds. Several polynomials were used to model the attitude data, and the residuals of the fittings obtained using different degrees are presented in table 3.1 and are plotted in figure 3.5.

<table>
<thead>
<tr>
<th>Polynomial Degree</th>
<th>rms residuals found between the model and data (rad)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>roll</td>
</tr>
<tr>
<td>2</td>
<td>6.8x10^-7</td>
</tr>
<tr>
<td>3</td>
<td>4.2x10^-7</td>
</tr>
<tr>
<td>4</td>
<td>3.7x10^-7</td>
</tr>
<tr>
<td>5</td>
<td>3.1x10^-7</td>
</tr>
<tr>
<td>6</td>
<td>2.7x10^-7</td>
</tr>
</tbody>
</table>

Table 3.1 - Fitting of polynomial models to the attitude data of a strip of 4 SPOT scenes.
Chapter 3 Orientation model of linear array imagery

Fig 3.5 - Residuals found fitting polynomial models to the attitude data of a strip of 4 SPOT scenes.

Longer attitude files were simulated extending the attitude variograms described by Westin [1991a] for longer periods of time. A first study was performed using attitude data simulated for a time span of approximately 60 seconds. Tests similar to the previous ones were carried out with this data, yielding the precisions presented in table 3.2 and also presented in figure 3.6.

<table>
<thead>
<tr>
<th>Polynomial Degree</th>
<th>roll</th>
<th>pitch</th>
<th>yaw</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>3.4x10^-7</td>
<td>3.1x10^-6</td>
<td>7.9x10^-7</td>
</tr>
<tr>
<td>3</td>
<td>1.5x10^-7</td>
<td>2.5x10^-6</td>
<td>4.4x10^-7</td>
</tr>
<tr>
<td>4</td>
<td>1.4x10^-7</td>
<td>2.5x10^-6</td>
<td>4.4x10^-7</td>
</tr>
<tr>
<td>5</td>
<td>8.6x10^-8</td>
<td>2.1x10^-6</td>
<td>3.1x10^-7</td>
</tr>
<tr>
<td>6</td>
<td>8.6x10^-8</td>
<td>2.0x10^-6</td>
<td>3.0x10^-7</td>
</tr>
</tbody>
</table>

Table 3.2 - Fitting of polynomial models to variogram derived attitude data.
Chapter 3 Orientation model of linear array imagery

Fig 3.6 - Residuals found fitting polynomial models to variogram derived attitude data.

However, the orientation model described in this study is able to handle longer strips of data. The variograms derived for SPOT by Westin [1991a] were thus used to create very long files of attitude data, simulating a continuous time span of about 750 seconds. Tests were performed to check the fitting of polynomial models to this attitude data. The results are presented in table 3.3 and plotted in figure 3.7.

<table>
<thead>
<tr>
<th>Polynomial Degree</th>
<th>rms residuals found between the model and data (rad)</th>
<th>roll</th>
<th>pitch</th>
<th>yaw</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td></td>
<td>3.1x10^{-6}</td>
<td>3.7x10^{-6}</td>
<td>2.7x10^{-6}</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>1.4x10^{-6}</td>
<td>2.7x10^{-6}</td>
<td>1.5x10^{-6}</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>1.3x10^{-6}</td>
<td>2.6x10^{-6}</td>
<td>1.5x10^{-6}</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>8.5x10^{-8}</td>
<td>2.3x10^{-6}</td>
<td>1.1x10^{-6}</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>7.6x10^{-8}</td>
<td>2.2x10^{-6}</td>
<td>1.0x10^{-6}</td>
</tr>
</tbody>
</table>

Table 3.3 - Fitting of polynomial models to variogram derived attitude data for a time span of approximately 750 sec.
Chapter 3 Orientation model of linear array imagery

Fig 3.7 - Residuals found fitting polynomial models to variogram derived attitude data for a time span of approximately 750 sec.

The SPOT attitude data provides information at intervals of approximately every 83 lines. This frequency on the attitude data file was adopted/used for the two first tests, on short data strips. However, for the third tests, which took a very long strip of attitude data, the fitting performed considered attitude data every 450 lines. Tests were also performed for an 83 line frequency without any significant improvement observed. In fact, the attitude modelling process became very time consuming with the fit improving by less than 1% of the data presented in table 3.3.

CNES [SPOT Manual] refers to an accuracy of $10^{-6}$ degrees of the attitude measurement system. The findings obtained using the polynomial approach for the attitude modelling can thus be considered independent from the errors made by the measurement system. The tests carried out on very long strips with data simulated using Westin’s variograms can thus be assumed to be very close to those expected had real attitude data been used instead.

The evident conclusion from a comparison of the results between tables 3.1 and 3.2 is that a higher precision of the order of 10% is achieved when Westin’s variograms are used to form the raw attitude data. This is a very important result that may influence the results on tests to be performed with this simulated data.
An additional test was performed to check the behaviour of polynomials when modelling very long arcs of attitude data. In this test, the same attitude data used for the third test was used, considering a 450 lines frequency rate. The attitude model obtained was then compared with data for the same orbit, at an 83 line frequency rate, the results of this test being presented in table 3.4.

<table>
<thead>
<tr>
<th>Polynomial Degree</th>
<th>rms residuals found between the model and data (rad)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>roll</td>
<td>pitch</td>
</tr>
<tr>
<td>2</td>
<td>3.0e-6</td>
<td>3.5e-6</td>
</tr>
<tr>
<td>3</td>
<td>1.2e-6</td>
<td>2.8e-6</td>
</tr>
<tr>
<td>4</td>
<td>1.3e-6</td>
<td>2.6e-6</td>
</tr>
<tr>
<td>5</td>
<td>7.2e-8</td>
<td>2.0e-6</td>
</tr>
<tr>
<td>6</td>
<td>7.7e-8</td>
<td>2.0e-6</td>
</tr>
</tbody>
</table>

Table 3.4 - Fitting of polynomial models to variogram derived attitude data at 450 lines frequency rate, compared with attitude data derived at 83 line frequency rate.

Fig 3.8 - Residuals found fitting polynomial models to variogram derived attitude data at 450 lines frequency rate, compared with attitude data derived at 83 line frequency rate.
Chapter 3 Orientation model of linear array imagery

From analysis it may be concluded that a polynomial approach can be used to model the attitude data with sufficient accuracy, because the attitude variations of the satellite’s platform are very smooth. Hence, the coefficients of higher degrees of the polynomials are very small and very small oscillations occur.

When no header data is available, the attitude parameters and their variation with time are initially set to zero.

3.4.4. Initial estimation of the time displacement parameter

The most efficient and accurate way of estimating the time displacement between two images is to measure the time span between the time of acquisition for each. This is easily done by comparing the time of acquisition for both images as given on the header data file. Knowing the time taken to image each line, which is specified for each sensor, $\Delta t$ may be easily transformed into number of lines.

For the case when no header data is available, an alternative procedure must be introduced to the algorithm to initially estimate $\Delta t$. The time displacement parameter can be estimated using equation [3.52], obtained from a first approximation of the geometry illustrated in Fig 3.4. Although each image may cover very long areas acquired during several minutes, the time difference between two along track images is usually less than a minute. Hence, the curvature of the Earth is not considered for a first approximation.

![Fig 3.9 - First approximation of the time displacement parameter.](image-url)
The time displacement parameter, \( \Delta t \), may be estimated using equation [3.52]:

\[
\Delta t = H \cdot (\tan\alpha_1 - \tan\alpha_2) \cdot s
\]  

[3.52]

In equation [3.52], \( H \) is the estimated altitude of the satellite; \( s \) is the scale factor estimated using the physical characteristics of the sensor; and \( \alpha_1 \) and \( \alpha_2 \) are the viewing angles of the two images under consideration.

The value of \( \Delta t \) is referenced to the first line of the first image. This may be further improved by adding the difference in line number of a conjugate point identified in both images. When such a point is not available, a lower weight is given to the parameter, and poorer models should be expected. In this case, large oscillations may occur and the height of the model may be severely affected. A better model may be obtained orientating the images separately.

### 3.4.5. Estimation of the weighting matrix, \( W_{XX} \)

Whenever the initial values of the orientation parameters are estimated using the header data information, the weighting matrix, \( W_{XX} \), is formed using the standard deviations of the errors between the supplied data and the estimated parameters. For the case of the attitude parameters, the header attitude data is compared with the computed attitude model and a root mean square of the residuals is calculated. If this is larger than the specified accuracies of the measurement system, then this value is adopted to form the weighting matrix. Otherwise, the specified mean standard deviation is adopted.

When the header data is not used, or is not available, the weighting matrix may still be formed \textit{a priori}. However, the standard deviations will be estimated and entered into the computations by the user.

Another method may be adopted. The weighting matrix may be formed \textit{a posteriori}, using the co-variance matrix of the orientation parameters. This is calculated at an intermediate stage during the inversion of the normal matrix of the observation
equations. The co-variance matrix describes possible correlations between the orientation parameters, and weights can be attributed accordingly. The a posteriori weighting matrix may be useful when the data is not reliable or the operator has no feeling about their precision.

These two options may also be useful when oscillations occur and the iterative process does not converge. Different weights may then be tested until convergence is achieved. The two methods are tested for various models in chapter 7.

3.5. Orientation of blocks of linear array imagery

3.5.1. Identification of strip and image numbers

During the data reading process, measurements are assigned to an image and its respective strip. This is recorded on the control data file as in the example presented in Appendix A. Whenever necessary, a pointer is used to check whether the GCP was identified on the strip and image under consideration during each particular computation. This procedure allows input of the ground control identified on several images through a unique file. This also allows the identification of conjugate points, for which ground coordinates are unknown, though their image coordinates are given for at least two images.

Additionally, the use of conjugate points may be particularly important, contributing to improve the relative orientation of the model [Hofmann and Müller, 1987]. Institutions such as IGN have already developed formulae to accommodate conjugate points in the orientation of SPOT stereopairs [Guichard and Pikeroen, 1988; Veillet, 1988]. Hence, the introduction of conjugate points in the orientation process has warranted special attention. Tests were performed using conjugate points and results are reported in chapter 8.
3.5.2. Blocks of stereo models

As referred to in the previous section, control points can be introduced to the computation through a unique file, independent of the image and strip to which the measurements belong. A pointer is used to keep track of this information, and to introduce the respective observation equations for the orientation of the corresponding strip. This feature allows the combination of simultaneous ALTI and ACTI data. Moreover, it is possible to orientate blocks of stereo models using common ground control to the various strips under consideration or not, as the case may be. These may or may not cover overlapping areas.

Although strips may be orientated using independent ground control, common GCPs must be used to link them. The use of more than two images to form a stereomodel, and more than one strip, theoretically strengthens the orientation [Kratky, 1989a].

In summary, it is possible to combine LAI from different sensors to form hybrid stereo models. However, only data from satellite sensors may be considered due to the assumptions used in forming the orientation algorithm. Other LAI obtained from lower altitude sensors may suffer more complex effects not considered by the orientation model presented in this thesis.

3.5.3. Ground coordinates of points identified in the imagery

Once the number of strips and images for each strip is known, the model is orientated. Afterwards, the ground coordinates of points identified on at least two images may be computed using the final estimated orientation parameters.

Each point identified for each image will give the set of equations 3.16. In order to separate all the unknowns into the second term, the system of equations can be written as [3.53].

$$
\begin{bmatrix}
X_s \\
Y_s \\
Z_s
\end{bmatrix} =
\begin{bmatrix}
1 & 0 & 0 & a \\
0 & 1 & 0 & b \\
0 & 0 & 1 & c
\end{bmatrix}
\begin{bmatrix}
X_A \\
Y_A \\
Z_A \\
S
\end{bmatrix}
$$

[3.53]
where

\([X_A, Y_A, Z_A]^T\) are the unknown geocentric coordinates of the ground point A;
\([X_S, Y_S, Z_S]^T\) are the geocentric coordinates of the sensor at the time of imaging A;
s is the scale factor for the point; and

\[
\begin{bmatrix}
a \\
b \\
c
\end{bmatrix} = R \begin{bmatrix}
0 \\
y \\
-s
\end{bmatrix}
\]  \[3.54\]

where

\(R\) is the rotation matrix \([3.13]\) to transform from sensor to geocentric coordinates;
\(y\) is the sample coordinate of the imaged point A in the image being considered;
and

\(f\) is the principal distance of the camera.

Measurements of one point identified on each image yield a set of three equations with four unknowns: the three geocentric coordinates \([X_A, Y_A, Z_A]^T\) and the scale factor \(s\) \([3.53]\). A point identified in at least two images will thus form 6 equations. If the point is identified in \(n\) images, there will be \(3n\) equations to solve the \(3+n\) unknowns: the ground coordinates of the point plus the scale factors of the \(n\) images. The system to solve will take the form given by equations \([3.55]\)

\[
\begin{bmatrix}
P_1 \\
\vdots \\
P_n
\end{bmatrix} = \begin{bmatrix}
X_A \\
Y_A \\
Z_A \\
s_1 \\
\vdots \\
s_n
\end{bmatrix} \begin{bmatrix}
P_1 \\
\vdots \\
P_n
\end{bmatrix}
\]  \[3.55\]

where the positions \(P_i\) of the satellite are given by equation 3.54

\[
P_i = \begin{bmatrix}
X_S \\
Y_S \\
Z_S
\end{bmatrix}
\]  \[3.56\]

and where \(s_i\) is the scale factor for the point in image \(i\).

Matrix \(M\) will have \(3n\) rows and \(3+n\) columns, according to the number of observation equations for the \(n\) images. The least squares adjustment method is used to solve the system and the geocentric coordinates \([X_A, Y_A, Z_A]^T\) of point A are output.
The same set of equations may be used either for checking the precision of the orientation model or to compute the ground coordinates of points identified in the imagery. To check the precision of the orientation model, the calculated ground coordinates of some check points are compared to their known coordinates.

3.6. Conclusions

The orientation model described in this chapter is a versatile model for the orientation of LAI from satellite platforms. The algorithm was implemented on a Micro VAX II / GPX computer and allows the simultaneous orientation of data acquired by different types of linear array sensors. It may also orientate blocks of ACTI and ALTI data, over common areas as desired.

The time displacement parameter is introduced to the model to link imagery taken during the same orbit. This allows the orientation of ALTI with a reduction on the ground control requirements. Dowman et al. [1991] state that a SPOT stereopair may be orientated within 15m precision using an orbital parameter approach with a minimum of six control points, and if no header data is used. The use of the time displacement parameter helps in reducing the number of control points required for the orientation of an along track stereopair under the same conditions. In this case, the orbital parameters are the same for both images and so there is only one additional orientation parameter per image considered for each orbit. Hence, it is theoretically possible to orientate an along track stereo pair using all the orientation parameters, and no header data, with a minimum of three GCPs.

When available, the information given by the header data may be used to:
- generate attitude models over the time span of image acquisition;
- estimate the initial orbital parameters used in the orientation process;
- extract auxiliary data needed in the orientation process;
- extract information used to generate the weighting matrix of the orientation parameters;
and
Chapter 3 Orientation model of linear array imagery

- estimate the time displacement between images taken during the same orbit pass.

The weaknesses of the approach described are basically twofold. Firstly, there is a high correlation between the pitch and the time displacement parameter. Therefore, the accuracy of *a priori* information is very important for the convergence of the iterative process. It is possible to orientate the model without using the constrained solution, but this may be highly affected by these correlations possibly giving rise to oscillations during the iterative process.

The second problem is related to the former and stems from the problem of obtaining an accurate initial estimate of the time displacement parameter. This is possible when header data is available. Errors in the initial estimation may propagate during the iterative process resulting in a poorer orientation model. To avoid this, the ground control must be carefully chosen where no header data is available. A minimum of one control point must then be identified simultaneously on all the images under consideration.

This model allows the orientation of discontinuous SPOT stereopairs, and uses the time displacement parameter as a pass-processing parameter. The SPOT scenes acquired during the same orbit can be declared as belonging to the same strip, giving them different image numbers, and the same along and across track angles. Theoretically, non-continuous stereopairs can be orientated with a minimum of 6 control points per strip and no header data information. The geometry of an extended image can thus be rectified with as few control points as for only one scene if orbital constraints and attitude measurements are properly considered.

This model also has the advantage of taking account of the accuracy of the control data during the orientation process. Larger weights are assigned to more precise control.

It is very important to know that only satellite imagery may be adequately orientated using this method because a smooth variation of the attitude and position parameters is assumed. Higher frequency variations of the attitude parameters may be considered in the model, to solve the problem. This results in additional unknowns, which may become very expensive in terms of the amount of GCPs required.
Chapter 4.

Data simulation and validation

4.1. Simulated data

4.1.1. Introduction

Presently, OPS is the only satellite sensor launched capable of producing along track linear array imagery (ALTI). Other high resolution sensors such as OMI and ASTER are expected to be launched in the late 1990s and the MOMS-02 airborne sensor was launched on the 26th of April 93, while OPS data has only just became available. Consequently, all three sensors have been simulated for testing purposes. A comparison between the accuracies obtained orientating simulated and real OPS data was initially intended. Such tests would allow a more accurate prediction of the orientation for future real OMI and ASTER data. Possible discrepancies between the results obtained using simulated and real OPS data could easily be extrapolated for the future OMI and ASTER missions. However, it was impossible to validate the simulation of ALTI data due to the non availability of real data. Hence, the data validation performed for SPOT data was assumed for ALTI data.

Heipke and Kornus, [1991] refer to the intention of CNES to introduce along track stereo capability to future SPOT systems. Taking account of this possibility, data was additionally simulated considering a theoretical SPOT sensor with the SPOT characteristics and along track capability. No further information was found on possible values of the along track angles to be adopted on those future SPOT missions. So, these were chosen to provide a comparison between the simulated SPOT along track models (SPOT-like models) and the other simulated sensors. This would also allow the
comparison between the expected accuracy orientating along track imagery (ALTI) versus existing SPOT data.

4.1.2. Geometric characteristics of simulated sensors

The simulation of OPS, ASTER and OMI data was carried out considering the respective published characteristics and previously described in section §2.8 [Arai, 1991; British Aerospace, 1991; MITI/NASDA, 1990]. The various parameters adopted both for their orbital positions and for the sensor physical characteristics are summarised on table 4.1, which is expanded from table 2.1.

<table>
<thead>
<tr>
<th>sensor</th>
<th>ASTER</th>
<th>OMI</th>
<th>OPS</th>
</tr>
</thead>
<tbody>
<tr>
<td>pixel resolution</td>
<td>15 m</td>
<td>5 m</td>
<td>18.3 x 24.2 m²</td>
</tr>
<tr>
<td>flying altitude</td>
<td>705 km</td>
<td>824 km</td>
<td>568 km</td>
</tr>
<tr>
<td>along track</td>
<td>0° nadir</td>
<td>20° back</td>
<td>0° nadir</td>
</tr>
<tr>
<td>viewing angles</td>
<td>29.7° forw</td>
<td>20° forw</td>
<td>15.3° forw</td>
</tr>
<tr>
<td>offset angles</td>
<td>0°</td>
<td>1° right</td>
<td>0°</td>
</tr>
<tr>
<td>B/H (=)</td>
<td>0.6</td>
<td>0.7</td>
<td>0.3</td>
</tr>
<tr>
<td>CCD elements</td>
<td>5,000</td>
<td>12,000</td>
<td>4,096</td>
</tr>
<tr>
<td>orbit inclination</td>
<td>98.6°</td>
<td>98.6°</td>
<td>98.6°</td>
</tr>
</tbody>
</table>

Table 4.1 - Characteristics of the ASTER, OMI and OPS sensors.

Although no offset is referred to by British Aerospace [1991], Chaloner [1992] referred to the introduction of an across track offset to the OMI system. This feature is considered in order to improve the overlap of an OMI stereopair from approximately 60% to 90%. However, the offset angles to be introduced were not quoted by Chaloner [1992]. Therefore, offsets of ±1° were adopted for the simulations of the OMI data, since a 90% overlap is obtained.
Several SPOT-like sensors data were simulated. Each of these sensors was assumed to have the basic characteristics of the SPOT sensor [Table 4.2], and additional along track capability similar to the three sensors ASTER, OMI and OPS. The characteristics of the simulated SPOT-like sensors are presented on table 4.3.

<table>
<thead>
<tr>
<th>REAL SPOT sensor (variable across track angle)</th>
<th>pixel res.</th>
<th>altitude</th>
<th>view. angles</th>
<th>B/H</th>
<th>CCD elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 m (P mode)</td>
<td>830 km</td>
<td>0.18° forw offset variable across</td>
<td>variable</td>
<td>6,000</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.2 - Characteristics of the real SPOT sensor.

<table>
<thead>
<tr>
<th>Simulated SPOT-like sensors (across track angle 0°)</th>
<th>sensor</th>
<th>view. angles</th>
<th>B/H</th>
<th>pixel res.</th>
<th>altitude</th>
<th>orbit inc.</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPOT-ASTER</td>
<td>0° nadir</td>
<td>29.7° forw</td>
<td>0.6</td>
<td>10 m</td>
<td>830 km</td>
<td>98.6°</td>
</tr>
<tr>
<td>SPOT-OMI</td>
<td>20° back</td>
<td>20° forw</td>
<td>0.7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SPOT-OPS</td>
<td>0° nadir</td>
<td>15.3° forw</td>
<td>0.3</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4.3 - Characteristics of SPOT-like sensors with simulated along track capability.

4.1.3. The transformed OEEPE test simulated data

The simulation was based on real ground control data previously used on the OEEPE test on “Block Triangulation of SPOT Data” [Dowman et al., 1991]. The control from strip A of the referred data was used, covering a region on South East France about 60km width and 240km long, extending from Grenoble to Marseille. A sketch of this area is shown on figure 4.1. For this region, 106 GCPs were provided by IGN. The image coordinates for these control points were simulated for the different sensors described in tables 4.1 and 4.3.
Chapter 4. Data simulation and validation

A vertical orbit for the strip was calculated considering the two SPOT images provided for the OEEPE test. This was achieved by rotating the computed orbits of the real SPOT data to a vertical looking orbit and adjusted to the mean path of the ground control. This last adjustment was performed keeping the orbit inclination fixed, to maintain the approximate specifications given for the sensor.

4.1.4. The long strip simulated data

The OEEPE strip presented in §4.1.3 was extended north and southwards from Sweden to Algeria, as sketched in figure 4.2. This new simulated strip is approximately 3800km long. Because no ground control data was available for such a long area, this was also simulated.
This simulation was carried out by creating points on the Hayford ellipsoid [Snyder, 1987], along the sub satellite path of the vertical estimated orbit obtained from the OEEPE data. This was extended to both sides of that path, east and westwards, and lifted to a mean height of approximately 500 meters above the ellipsoid. The resulting data set is continuous along the flight path, not recognising existing water bodies such as the Mediterranean sea. Simulated control lying on water areas was thus later excluded from the data sets.

Not all the 522 ground points generated on this strip will be used simultaneously for each orientation. After the simulation procedure, the points whose image coordinates do not lie within the dimensions specified for the linear array are eliminated. A few points are chosen to become ground control, while the remaining will be used as check points. The algorithm used to simulate the image coordinates of the simulated ground data for each sensor is presented in the next section [§4.2].
4.2. Simulation algorithm

4.2.1. Introduction

Simulating the OPS, ASTER, OMI and SPOT-like imagery is based on estimating the image coordinates, line and sample numbers, for control points of known ground coordinates. This calculation was simplified for this study by considering SPOT data used on the OEEPE test [§4.1.3]. The ground control used during the OEEPE test lies along a flight path of a satellite whose orbital inclination is approximately 98°.

The orbital parameters of an orbit passing vertically above the control were estimated by rotation of the left and right SPOT images given for the OEEPE tests. This was later adjusted to a sub-satellite ground flying track averaged to the distribution of the control on the ground. This adjustment was carried out allowing only very small changes to most of the orbital parameters. The true anomaly and the longitude of the ascending node were freely adjusted. Attitude data was modelled using Westin's variograms derived from SPOT data.

For an eventual simulation of linear array data with a non-zero across track angle, the same procedure was applied. However, in this case, the two SPOT images considered in the OEEPE test are not initially rotated to the vertical. Instead, they are rotated to the pre-defined angle and adjusted assuming the desired perspective view.

4.2.2. Basis of the simulation algorithm

The reverse collinearity equations for LAI are used to find the image coordinates corresponding to any known ground control. These are given by equation [4.1].

\[
\begin{bmatrix}
X \\
Y \\
-Z_f
\end{bmatrix} = \frac{1}{s} \cdot R_A^T R_0^T R_m^T \begin{bmatrix}
X_A - X_S \\
Y_A - Y_S \\
Z_A - Z_S
\end{bmatrix}
\]  

[4.1]
where

\[
[x, y, -f]^T \quad \text{are the image coordinates of the point;}
\]

\[f\] is the principal distance of the lens;

\[s\] is the scale factor;

\[[X_A, Y_A, Z_A]^T\] are the geocentric coordinates of the control point \(A\);

\[[X_S, Y_S, Z_S]^T\] are the geocentric coordinates of the sensor;

\[R_m\] is the rotation of the viewing angles;

\[R_o\] is the rotation for the orbital parameters; and

\[R_A\] is the rotation of the attitude parameters.

Once the orientation parameters are known, so are the matrices \(R_m, R_A, R_o\). During the simulation process, the sensor position \([X_S, Y_S, Z_S]^T\) and the principal distance \(f\) are also known. The image coordinates \([x, y]\) can thus be calculated, once the ground coordinates \([X_A, Y_A, Z_A]^T\) of the control point \(A\) are given.

As it was previously stated in section 3.2.1, the image is one dimensional and the line number, \(x\), considered in formula [4.1] is equal to zero. The orientation varies continuously, depending on the time of imaging, i.e. the line number, which is initially unknown.

The basic method of finding the solution of this problem was first presented for Mapsat by Snyder [1982]. The approach consists of an iterative method of solution for the reverse equations [4.1]. The collinearity condition is satisfied when the ground point vector \([X_A - X_S, Y_A - Y_S, Z_A - Z_S]^T\) is collinear with the image vector \([x, y, -f]^T\). If the estimated value of the time of imaging is not correct, the image vector will intersect the focal plane at a position where \(x\) is not equal to zero [Fig 4.3]. In this case, the estimate line number must be revised until a good approximation is found.

The process of estimation of the correct time of imaging corresponding to each set of ground coordinates is reduced by making use of an iterative process which considers a combination of more than one estimation method.
4.2.3. Direct extrapolation of the parameters

This is an iterative method of improving the value of the true anomaly based on the erroneous x coordinate found during each previous iteration. First, the error $\Delta x$ corresponding to the current orientation parameters is estimated using the reverse equations. Afterwards, the along track angular error $\gamma$ in the image space is calculated by equation [4.2]

$$
\gamma = \arctan \left( \frac{\Delta x}{f} \right) \quad [4.2]
$$

where

- $\Delta x$ is the error in x found solving the collinearity equations; and
- $f$ is the principal distance of the camera.

Finally, using the sine rule, the correction $dF$ is estimated by equation [4.3]


\[
dF = \arcsin \left( \sin \gamma \cdot \frac{X_S}{X_A} \right) - \gamma
\]

[4.3]

where

- \(X_S\) is the estimated geocentric distance of the sensor; and
- \(X_A\) is the geocentric distance of the ground control A.

The value of \(dF\) is added to the value of the true anomaly \(F\) used in the previous iteration and the reverse equations are recalculated.

### 4.2.4. Interpolative estimation of the parameters

The previous method alone no longer yields the correct value of \(x\) after two iterations, specially where very long strips of data are encountered. A third estimation of the true anomaly is made by interpolation between the first two values and their corresponding \(x\) coordinates.

When very long strips of data are considered, the solution may not converge by this third iteration. In this case, the iterative process is repeated using the direct extrapolation approach combined with the interpolative estimation of the parameters until convergence is achieved.

The iterative process is run until a correction smaller than 0.0001mm is encountered for the condition \(x=0\). This correlates to an error smaller than 0.01 in line number for the case of SPOT imagery.

### 4.2.5. Estimation of the line number \(x\).

The time of acquisition of a particular point is unknown until the condition \(x=0\) is satisfied, as is the line number \(x\). Instead, the true anomaly is used to describe the position of the satellite at the time of imaging. This is so that \(x\) can be calculated using equation [4.4].

\[
x = \frac{(F - F_0)}{F'}
\]

[4.4]
where
\[ F \] is the true anomaly at the time of imaging;
\[ F_0 \] is the true anomaly corresponding to the first line of the image; and
\[ F' \] is the rate of change of \( F \) with time.

The value of the image coordinate, \( y \), is then calculated using the reverse collinearity equations [4.1]. This will correspond to a value of \( y \) computed for the time of acquisition for which the output value of \( x \) will equal zero.

### 4.2.6. Simulation of attitude and positioning data

The attitude data used during the simulation process described above is derived from Westin's variograms, and these were derived from SPOT data [Westin, 1991a]. However, this data is smoother than real data. Hence, random errors with standard deviations defined by the user are added to the attitude data given by Westin's variograms to simulate more realistic attitude data sets. In section §6.8 this feature will be used to study the influence of the precision of the attitude data to the orientation modelling.

Other errors may also occur from small variations in the orientation parameters, that might not have been considered during the simulation process. Again, these can be simulated by adding random errors to the orientation parameters and to the output positioning data alike.

### 4.3. Adding pseudo-errors to the simulated data

#### 4.3.1. Introduction

A point of major concern during the simulation of image coordinates for the various sensors under investigation is the accuracy of the output image coordinates. As stated in §4.2.5, the simulation was estimated to a 0.01 line/sample precision for the SPOT
sensor. However, when identifying points in an image, an operator is not able to measure the line and sample numbers of the point to the same precision.

Heipke and Kornus [1991] refer to an accuracy of 12\(\mu\)m for the error of measurements in point identification on SPOT imagery. This corresponds to approximately 1 pixel resolution, reflecting the problems of point identification and measurement previously mentioned. A more descriptive categorisation of the quality of control identified in SPOT imagery is given by Rodriguez et al. [1988] and Gugan [1991].

Rodriguez et al. [1988] divide the image measurements into three categories as follows:

1. points correctly defined on the ground and clearly identifiable on the image;
2. points correctly defined on the ground but not very well defined on the imagery; and
3. points poorly defined or virtually invisible on the imagery.

However, this division is mainly a qualitative description of the data. Gugan [1991] presents a more quantitative definition of the quality of the control, the percentage of points falling in each category being:

1. 17\% very good control points, measured to better than half a pixel;
2. 38\% good points, measured to about one pixel accuracy;
3. 22\% average quality, taking into account points with some doubt as to their exact position;
4. 17\% poorly defined points; and
5. 6\% points identified in regions of very poor image quality.

The latter classification was adopted as standard basis for the simulation process described in this thesis, since it is more descriptive of the errors found in real data. It gives a quantitative estimation of the distribution of these errors by classes, and can thus be written in mathematical/logical expressions.

4.3.2. Adding pseudo-errors to the simulated image coordinates

Pseudo-errors of identification and measurement of the points in the simulated images were added to the image coordinates considering an error of location of 0.95 pixel, and a
normal distribution with standard deviation 0.7 in line and 0.7 in sample. A routine in
the program generates values with normal distribution. However, left alone, these values
are always generated in the same order. Hence, everytime the simulation program is run,
the same pseudo-errors are added to the same image coordinates. To avoid this from
happening, an auxiliary integer is initially introduced by the user. This integer
corresponds to the number of times that the routine will be run prior to the addition of
the generated pseudo-errors to the image coordinates. Changing the integer, the list of
pseudo-errors to add to the image coordinates will vary.

A study was carried out after applying the above procedure to 2000 simulated points
to check the quality of the measurements. The errors added to the simulated data
distributed the points into the five adopted categories shown in table 4.4.

<table>
<thead>
<tr>
<th>categories</th>
<th>interval of pixel accuracy [pixel]</th>
<th>points found in each category (%)</th>
<th>distribution referred by Gugan [1991] (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>[0 ; 0.5]</td>
<td>25.8</td>
<td>17</td>
</tr>
<tr>
<td>2</td>
<td>[0.5 ; 1]</td>
<td>28.6</td>
<td>38</td>
</tr>
<tr>
<td>3</td>
<td>[1 ; 1.5]</td>
<td>24.2</td>
<td>22</td>
</tr>
<tr>
<td>4</td>
<td>[1.5 ; 2]</td>
<td>15.7</td>
<td>17</td>
</tr>
<tr>
<td>5</td>
<td>[2 ; -&gt;]</td>
<td>5.7</td>
<td>6</td>
</tr>
</tbody>
</table>

Table 4.4 - Distribution of pseudo-errors added to 2000 simulated points and
distribution referred by Gugan [1991].

A comparison between the distribution of the pseudo-errors added to the simulated data
with the accuracies referred by Gugan [1991] [table 4.4] shows a good approximation to
the errors of identification and measurement obtained with real data. The percentage of
simulated points with less than 1 pixel error is similar to that found by Gugan [1991].
The percentages found for the other classes are also very similar for both sets of data.
Hence, this method was adopted to simulate errors on the image coordinates of the
simulated control.
4.3.3. Adding pseudo-errors to the ground control coordinates

When the image coordinates of the ground control are simulated for any specific sensor, their corresponding ground coordinates are error-free, according to the simulation process. In a real situation, the ground coordinates of the control are extracted either from maps, aerial photographs, or other types of data. Therefore, they are affected by errors of identification and measurement. Hence, pseudo-errors must be added to the ground coordinates of the simulated control in order to simulate a real situation.

Usually, the errors committed when identifying control on a map or aerial photograph have different precision in planimetry and in altimetry, e.g. ground control given by IGN for the OEEPE test [Dowman et al., 1991]. For this reason, simulated errors are also added to the UTM coordinates of the control. The precisions in planimetry and in altimetry of the ground control can be specified by the user during the simulation process. This can be entered in metres, and will be considered as the standard deviation of the errors added to the ground coordinates.

4.4. Validation of the LAI orientation model

Prior to any test, it is necessary to check if the LAI program works correctly. The method adopted for validation of the LAI orientation model consisted in orientating real SPOT data with both Gugan-Dowman's program (available at UCL) and the LAI program. The OEEPE SPOT data was used, introducing the same ground control to both programs [Dowman et al., 1991]. The residuals found orientating the same data with the two programs are given in table 4.5, and are presented for height and planimetry in figure 4.4.

The differences encountered between the two orientations are small enough to justify the validation of the LAI orientation program. One may note the smoother variation of
the residuals in height of the models orientated with the LAI program. However, is also observed a worsening of the accuracy in plan for a small number of control points.

<table>
<thead>
<tr>
<th>number of control pts</th>
<th>rms (m) using LAI orientation</th>
<th>rms(m) using Gugan-Dowman’s orientation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>H</td>
<td>2D</td>
</tr>
<tr>
<td>16</td>
<td>6.4</td>
<td>10.3</td>
</tr>
<tr>
<td>13</td>
<td>6.7</td>
<td>12.8</td>
</tr>
<tr>
<td>12</td>
<td>6.6</td>
<td>11.3</td>
</tr>
<tr>
<td>11</td>
<td>6.8</td>
<td>11.0</td>
</tr>
<tr>
<td>8</td>
<td>6.8</td>
<td>12.4</td>
</tr>
<tr>
<td>6</td>
<td>7.4</td>
<td>16.5</td>
</tr>
</tbody>
</table>

Table 4.5 - Residuals obtained orientating real SPOT data with Gugan-Dowman’s and with the LAI programs.

Fig 4.4 - Residuals in height and in plan of modelling OEEPE SPOT data using Gugan-Dowman’s and the LAI orientation programs.
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The residuals found after orientating the SPOT model are plotted in figures 4.5 and 4.6, which were obtained with the 12 GCPs configuration. A random configuration of these residuals stems from the analysis of these plottings, for both orientations. The LAI orientation program thus orientates SPOT models with accuracies comparable to those obtained to Gugan-Dowman’s program and with similar random residuals over the model.

To test the capability of orientation of data using on-board measured data, the same models were orientated using the SPOT header data. The results from such tests are presented in table 4.6.

![Fig 4.5a](image1.png)  ![Fig 4.5b](image2.png)

Fig 4.5 - Plotting of the residuals (a) in plan and (b) in height for 106 check points, of a SPOT model orientated using Gugan-Dowman’s orientation program.
Chapter 4. Data simulation and validation

Fig 4.6 - Plotting of the residuals (a) in plan and (b) in height for 106 check points, of a SPOT model orientated using the LAI orientation program.

<table>
<thead>
<tr>
<th>number of control pts</th>
<th>rms (m) using model without header data</th>
<th>rms (m) using model with header data</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>H</td>
<td>2D</td>
</tr>
<tr>
<td>16</td>
<td>6.4</td>
<td>10.3</td>
</tr>
<tr>
<td>13</td>
<td>6.7</td>
<td>12.8</td>
</tr>
<tr>
<td>12</td>
<td>6.6</td>
<td>11.3</td>
</tr>
<tr>
<td>11</td>
<td>6.8</td>
<td>11.0</td>
</tr>
<tr>
<td>8</td>
<td>6.8</td>
<td>12.4</td>
</tr>
<tr>
<td>6</td>
<td>7.4</td>
<td>16.5</td>
</tr>
</tbody>
</table>

Table 4.6 - Residuals of SPOT models orientated with the LAI program and using or not the header data.
4.5. Data validation

4.5.1. Introduction

Prior to any testing, it is necessary to check the validity of the simulated data. The eventual differences found may later be used as reference. For the purpose, it is necessary to validate the simulation of the ground control data and to validate the simulation of the attitude data. The following method was adopted for data validation:

1. assessment of the residuals obtained modelling error-free simulated data;
2. comparison of the results obtained orientating models using the same control configuration on both real and simulated SPOT data covering the same area; and
3. study of the differences obtained using simulated and real attitude data.

These tests were carried out using the orientation model described in chapter 3 of this thesis and the simulation algorithm previously described.

4.5.2. Validation of the error free simulated data

The image coordinates of the GCPs given by IGN for the OEEPE test were simulated for the SPOT orbits considered on that test [Dowman et al., 1991]. For a first test, the simulation was carried out considering a linear variation of the attitude parameters with time, and no pseudo-errors were added to the simulated image coordinates. The simulated images were orientated using both Gugan-Dowman's SPOT resection program and the LAI model derived in chapter 3.

The 3D residuals of the orientated models are presented in figure 4.7. Similar results were found with the LAI orientation program and Gugan-Dowman's model, for the same error-free simulated data. Theoretically, the output residuals of orientating such images should be close to zero, due to the assumptions made during the simulation. The residuals found result from the approximate formulation of the viewing system geometry.
4.5.3. Validation of the simulated image coordinates with pseudo-errors

The simulation of errors of identification and of measurements of the control was also validated using SPOT data simulated for the OEEPE test area. Errors were added to the simulated image coordinates, with a standard deviation of 0.7 in line and sample, as described in section §4.3.2. Both the real and the simulated SPOT data for the same area were orientated using the same control configuration and the same orientation model. In this case, the LAI orientation model was used.

The residuals obtained from orientating both sets of data are presented in table 4.7. Figures 4.8, 4.9 and 4.10 show the residuals obtained orientating real and simulated SPOT data in height, in planimetry (2D) and in three-dimensions (3D), respectively. All the residuals are given in UTM projection [Snyder, 1987].
Chapter 4. Data simulation and validation

<table>
<thead>
<tr>
<th>number of control pts</th>
<th>rms (m) with real SPOT data</th>
<th>rms (m) with simulated SPOT data</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>H</td>
<td>2D</td>
</tr>
<tr>
<td>16</td>
<td>6.4</td>
<td>10.3</td>
</tr>
<tr>
<td>13</td>
<td>6.7</td>
<td>12.8</td>
</tr>
<tr>
<td>12</td>
<td>6.6</td>
<td>11.3</td>
</tr>
<tr>
<td>11</td>
<td>6.8</td>
<td>11.0</td>
</tr>
<tr>
<td>8</td>
<td>6.8</td>
<td>12.4</td>
</tr>
<tr>
<td>6</td>
<td>7.4</td>
<td>16.5</td>
</tr>
</tbody>
</table>

Table 4.7 - Residuals obtained orientating real and simulated SPOT data with the same control configurations.

The differences observed between the models obtained with real and simulated data are in general smaller than 0.6m either in height, in planimetry or in 3D. The residuals obtained with simulated data are smaller than with real data, namely in height. The differences observed do not exceed 5% of the total residuals.

Fig 4.8 - Residuals obtained in height from orientating real and simulated SPOT data for the same area and using the same control configurations.
Fig 4.9 - Residuals obtained in planimetry from orientating real and simulated SPOT data for the same area and using the same control configurations.

Fig 4.10 - Residuals obtained in 3D from orientating real and simulated SPOT data for the same area and using the same control configurations.
From the residuals shown in table 4.7 and presented in planimetry in figure 4.9, an increase of the residuals is observed for the 13 GCPs control configuration. The occurrence may be justified by the distribution of control over the scene. This problem will be addressed in a later section of this thesis and is not important for the data validation. However, a similar increase occurred both for the real and the simulated data for the same control configuration. This ensures similar properties between the real and simulated data and the models they may form.

From the analysis of the tests performed it may be concluded that the models obtained orientating simulated data differ from the models obtained using real data by approximately 5%. This is the case for models obtained with no header data information.

4.5.4. Validation of the simulated attitude data

Tests were performed to determine to what extent the simulated attitude data is a good approximation of real attitude data, obtained from on-board measurements. The real and the simulated data for the OEEPE test area were orientated as in section §4.5.3, additionally using attitude data.

The residuals obtained orientating the real SPOT data with real attitude data, and the simulated SPOT data with the simulated attitude data, are presented in table 4.8, and plotted in figures 4.11, 4.12 and 4.13, for height, plan and 3D respectively.

<table>
<thead>
<tr>
<th>number of control pts</th>
<th>rms (m) with real SPOT data</th>
<th>rms (m) with simulated SPOT data</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>H</td>
<td>2D</td>
</tr>
<tr>
<td>16</td>
<td>6.5</td>
<td>10.3</td>
</tr>
<tr>
<td>13</td>
<td>7.1</td>
<td>12.8</td>
</tr>
<tr>
<td>12</td>
<td>6.4</td>
<td>11.0</td>
</tr>
<tr>
<td>11</td>
<td>6.6</td>
<td>11.0</td>
</tr>
<tr>
<td>8</td>
<td>6.7</td>
<td>11.7</td>
</tr>
<tr>
<td>6</td>
<td>6.9</td>
<td>15.0</td>
</tr>
</tbody>
</table>

Table 4.8 - Residuals obtained orientating real and simulated SPOT data with the same control configurations and additional real and simulated attitude information.
The differences encountered on these tests, using real and simulated SPOT data, were smaller than 1m, both in height and in planimetry. This implies a difference of approximately 20% in height and 10% in planimetry between real and simulated models. Comparing the differences in 3D, this becomes approximately 10%. As in the previous tests carried out without attitude data, the residuals obtained using simulated data tend to be smaller. However, the same variations occur for the various control configurations.

Fig 4.11 - Residuals obtained in height from orientating real and simulated SPOT data for the same area, using the same control configurations and real and simulated attitude data, respectively.
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Fig 4.12 - Residuals obtained in planimetry from orientating real and simulated SPOT data for the same area, using the same control configurations and real and simulated attitude data, respectively.

Fig 4.13 - Residuals obtained in 3D from orientating real and simulated SPOT data for the same area, using the same control configurations and real and simulated attitude data, respectively.
4.5.5. Precision of data validation

SPOT data were simulated for the OEEPE ground control data sets, considering two across track orbits of real SPOT images provided by IGN. Tests were performed with error-free simulated data, and very small residuals were obtained for each orientation. These are due to very small errors resulting from approximations to the viewing system geometry and the propagation of errors during the iterative process. Similar model precisions were obtained with both orientation programs used: Gugan-Dowman's space resection program and the LAI orientation algorithm.

The residuals encountered modelling SPOT data are usually larger than 9m [Dowman et al., 1991], whereas residuals encountered due to assumptions of the orientation algorithm are smaller than 1m [§4.5.2]. Hence, the residual errors intrinsic to the modelling algorithm can be considered negligible when compared to residuals due to errors in the data. Data affected by the errors given in §4.3.2, produce simulated models similar to the real SPOT models.

In all the tests considered, the models obtained using simulated data tend to have smaller residuals, although they have similar behaviour for the same control configurations adopted when orientating real data. The models obtained using simulated data do not differ by more than 10% from those obtained using real data.

4.6. Inversion of
residuals in planimetry for simulated data

4.6.1. The observed inversion of residuals in planimetry

Tests performed for data validation with real and simulated SPOT data, were presented in §4.4. The residuals obtained for simulated data were similar to those
obtained modelling real SPOT data, both in height and planimetry. However, it was not analysed how the differences in planimetry were distributed.

The residuals observed in planimetry resulting from the orientation of real and simulated SPOT data are presented in table 4.9. Figures 4.14a and 4.14b show the plottings of these residuals in UTM projection, in E and N, for real and simulated SPOT models respectively. Although the residuals in planimetry are very similar for real and simulated models [Fig 4.9], their distribution in E and N is very different [Figs 4.14 and 4.15].

The models obtained from the orientation of real SPOT data present larger residuals in E than in N [Fig 4.14a]. However, an inverted situation was found when orientating simulated SPOT data, for which larger residuals were obtained in N than in E [Fig 4.14b]. Several hypothesis were tested to explain this fact [§4.6.2].

<table>
<thead>
<tr>
<th>number of control pts</th>
<th>rms (m) with real SPOT data</th>
<th>rms (m) with simulated SPOT data</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>E</td>
<td>N</td>
</tr>
<tr>
<td>16</td>
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Table 4.9 - Residuals obtained in E and N [UTM projection] and in planimetry for real and simulated SPOT models using the same control configurations.
Fig 4.14 - Plotting of residuals obtained in E and N [UTM projection] for (a) real and (b) simulated SPOT models.

Fig 4.15 - Plotting of residuals obtained for real and simulated SPOT models (a) in E and (b) in N [UTM projection].
Chapter 4. Data simulation and validation

The residuals obtained orientating the same real SPOT data using Gugan-Dowman's orientation model are presented in table 4.10, and plotted in figure 4.16. A comparison with the models orientated using the LAI program show that the distribution of the errors in E and N is similar for the two methods.

<table>
<thead>
<tr>
<th>number of control pts</th>
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<th>rms (m) of Gugan-Dowman's orientation</th>
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Table 4.10 - Residuals obtained in E and N [UTM projection] and in planimetry for real SPOT models orientated using the LAI and the Gugan-Dowman’s program.

Fig 4.16 - Plotting of residuals obtained (a) in E and (b) in N [UTM projection] for real SPOT models orientated using the LAI and the Gugan-Dowman’s program.
Since the residuals in N and E obtained with real SPOT data are similar for the two different orientation methods, the inversion observed with simulated data has to be explained with basis on the characteristics of the simulated data.

4.6.2. Hypothesis to justify the observed inversion

*Hypothesis 1 - The inversion may result from error distribution on the ground coordinates.*

The ground control coordinates used to orientate the SPOT real data were affected by the errors stated by Dowman et al. [1991]. When error-free data was simulated for the same orbits of the OEEPE test, the output image coordinates correspond to ground coordinates, which are assumed error-free as well. To simulate the errors in the ground control, pseudo-errors were introduced to the simulated image coordinates as stated in §4.3. Additionally, random errors were also added to the GCPs UTM coordinates according to the accuracies described by Dowman et al. [1991]. The inversion registered in the residuals in E and N orientating real and simulated SPOT data may be due to the distribution of the pseudo-errors added to the UTM coordinates.

In order to test this hypothesis, several tests were carried out with simulated data whose UTM coordinates had been differently affected by variable errors. The pseudo-errors were always smaller than the accuracies specified by Dowman et al. [1991] but were made variable in E and N relative to each other. In other words, in some tests no error was added in E, in other tests no error was added in N, and other combinations were tested.

However, these tests did not influence the way the residuals of the final model would distribute in E and N. The same inversion was observed in all the cases and this hypothesis was abandoned.
Hypothesis 2 - The inversion may be due to the error distribution on the simulated image coordinates.

SPOT has an across track geometry and the N coordinate (UTM projection) coincides approximately with the satellite's flight direction, i.e., with the image coordinates. For the same reason, the E coordinate coincides approximately with the across track direction, and thus with the image coordinate y. Additionally, due to its side-looking geometry, the dimensions on the ground of the pixel in the y direction are larger than in the x direction. Hence, the same precision on measurements in x and y would theoretically give a more precise measurement on the ground in the along track direction (N) than on the across track direction (E). This would justify the distribution of the residuals orientating real SPOT data.

The pseudo-errors were similarly added to the simulated data, as described in §4.3. In other words, a similar pseudo-error added in line and sample, in pixels, would correspond to a larger error on the ground along the N coordinate than along the E coordinate. This effect is actually observed on real data models. However, the same effect is not observed on the simulated models. It was then tested if the inversion was related to the errors in line and sample. The pseudo-errors previously mentioned in §4.3.2 were added in different rates in line and sample. The total error added was such that the distribution through the different classes was kept approximately constant [§4.3.2].

However, the same inversion was observed for all the tests performed, and this hypothesis was not confirmed.

Hypothesis 3 - The inversion may result from the type of attitude data used during the simulation process.

The effect of the attitude parameters on the imagery was analysed in §2.3.3. Small variations in attitude were introduced during the simulation process, which may influence the computation of the simulated image coordinates. These will be studied in more detail in chapter 7, but some tests were carried out to test how they would affect the observed inversion.
Chapter 4. Data simulation and validation

For this purpose, different errors were added to pitch, roll and yaw, at different rates, and varying of about 1.0e-6 to about 1.0e-5 rad. These errors were added to the attitude angles obtained using Westin's variograms [§3.4.3], and the different simulated models were orientated using similar configurations. Slight variations were observed but the reported inversion was still present in all the cases, also excluding this hypothesis.

4.6.3. Summary

Tests using real SPOT data and Gugan-Dowman and LAI orientation model showed similar residuals in N and E for the same sets of data. Hence, hypotheses were tested in order to explain the inversion observed using simulated data.

None of the tested hypotheses explains the inversion observed for the residuals obtained in E and N (UTM) between real and simulated SPOT models. It may happen that this effect occurs as a joined effect of all the hypotheses tested above. Or it may be highly related to the identification and measurement of the image coordinates in stereoscopy. The relief perception may affect the measurements such that a higher precision in height may be obtained at expense of a lower precision in the across track direction, which corresponds approximately to the E coordinate.

Insufficient time was available for further investigation, and the inversion was not explained. The reader who plans to use this work should be aware of this difficulty.

4.7. Conclusions

Due to the non-availability of along track linear array data from satellite platforms at present, data had to be simulated for testing purposes. The ground control provided by IGN was used to simulate strips of LAI. The simulation method was described in this chapter and the data validated.
The error-free simulated data was used to prove the efficiency of the simulation algorithm and to test the LAI orientation program developed in chapter 3. The resulting errors were negligible, and were due to the assumptions made by the orientation method adopted and by the residuals propagated during the iterative process.

Tests carried out with real and simulated data showed a difference smaller than 5% between the models obtained with each set of data. Similar variations of residuals were observed for the same control configurations. Differences of about 10% were observed when real and simulated data attitude data were added to the orientation process.

Although the accuracies obtained in height and in planimetry were very similar for simulated and real models, an inversion was observed in the planimetric coordinates E and N (UTM projection). A real SPOT data model gives better accuracies in E than in N. Contrary to this, the simulated SPOT model show better accuracies in N than in E, and with values inverted relative to those found for real data models. Several hypotheses were tested to explain the observed inversion. However, none of them was confirmed and the simulation procedure could not be corrected to prevent this effect on the simulated models.

This subject certainly needs further investigation. However, considering the similarity in planimetry achieved for real and simulated models [§4.5], the simulation was considered acceptable under the precision intervals mentioned below. However, it is important to keep in mind this inversion, and that no explanation was found out for its occurrence.

In summary, the results obtained show the reliability of the simulation algorithm for SPOT data, with 10% accuracy. These results were obtained by tests carried out with ACTI. However, the same accuracy was assumed for ALTI, although this was not tested for this type of data, due to non-availability of it.
Chapter 4. Data simulation and validation
Chapter 5.

Orientation of SPOT, ASTER, OMI and OPS simulated data

5.1. Introduction

One of the prime objectives of this thesis is to forecast the accuracy to be expected from modelling future along track imagery (ALTI) to be acquired from satellite platforms. In this chapter, simulated ASTER, OMI and OPS data are orientated using the LAI program, in order to forecast the accuracy of future real models. The tests were performed for stereopairs covering the OEEPE test area [§4.1.3]. The data was simulated as previously described in chapter 4.

The accuracies obtained during data validation for the SPOT simulated data were assumed to be the same for along track modelling. This means that the accuracy forecast for ASTER, OMI and OPS models obtained in the tests carried out with simulated data are assumed to be correct with 10% error.

Tests were performed with SPOT-like simulated data [§4.1.2] to make a comparison between the models obtained with SPOT real data and the future sensors ASTER, OMI and OPS.

The capability of the LAI program to orientate hybrid models and blocks of more than one pair of images is also tested. The hybrid models were formed either mixing images of along and across track imagery or different types of along track imagery.
5.2. Simulated data used on the tests

The GCPs provided by IGN for the OEEPE test [§4.1.3] were used for the simulation of ASTER, OMI, OPS and SPOT-like data. This control was used for these tests in order to compare the simulated models to the real SPOT model orientated in chapter 4.

Six control configurations as similar as possible to those adopted in §4.4 were used. This procedure eliminates the influence of the control configuration on the different models. The number of control points used varied from 16 to 6 with the configurations sketched in figure 5.1.

Fig 5.1 - Control configurations used for the orientation of ASTER, OMI, OPS and SPOT-like simulated models.

All the ground control used for these tests has an error in plan and in height with standard deviation 3m and 3m, respectively. The simulated image coordinates are all
affected by a pseudo-error with $\sigma=0.7$ in line and sample [§4.3.2]. Of all the GCPs, 106 were used as check points. In order to simulate a real situation, the check points were also affected by errors similar to those introduced to the ground control. No attitude data or initial positioning data was considered. All the models were orientated using only information given by the ground control and the auxiliary data file [Appendix A]. This is similar to the orientation of SPOT during the OEEPE test, thus allowing a comparison between the simulated models and the real SPOT data.

5.3. Orientation of ASTER, OMI and OPS simulated data

5.3.1. Orientation of ASTER simulated data

The residuals obtained from orientating ASTER simulated data are presented in table 5.1. The Figs 5.2a and 5.2b show the plotted residuals obtained in E and N (East and North in UTM projection), and in height, in plan and 3D, respectively. A situation similar to that observed for SPOT simulated models [§4.5] is observed for the ASTER simulated models, showing larger residuals in N than in E [Fig 5.3a].

<table>
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Table 5.1 - Residuals obtained orientating ASTER simulated stereopairs, using OEEPE ground control data and different numbers of control points.
The ASTER sensor has a pixel resolution of 15m and the 3D precisions obtained for a 16 and a 6 GCPs configurations are 30.4 and 31.9m, respectively. A best model was obtained with a 13 GCPs configuration. For this case, the vector error obtained was 29.1m. This is due to the best precision obtained in plan, since the same effect is not observed in height. The model with best height accuracy, 24.3m, was obtained with an 8 GCPs configuration. These results may only be explained by the distribution of the simulated errors in the image coordinates of the control.

The plotings of the residuals found with the 12 GCPs configuration are presented in figures 5.3a and 5.3b. These are random through the area covered by the model.

Fig 5.2 - Plotting of residuals obtained for simulated ASTER stereopairs (a) in E, N, and (b) in height, plan and 3D [UTM projection].
Fig 5.3 - Plotting of the residuals (a) in plan and (b) in height for 106 check points, of an ASTER model orientated using the LAI orientation program.

5.3.2. Orientation of OMI simulated data

The residuals observed orientating OMI simulated data are presented in table 5.2. The residuals obtained in E and N are plotted in figures 5.4a, and 5.4b showing the residuals in height, plan and 3D. Similarly to what was previously observed for ASTER and for the SPOT simulated models, larger residuals were obtained in N than in E [Fig 5.4a] [§4.5].

Figures 5.5a and 5.5b show the sketch of the residuals obtained in 106 check points, after orientation of the model with 12 GCPs.
Chapter 5. Orientation of SPOT, ASTER, OMI and OPS simulated data

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Table 5.2 - Residuals obtained orientating OMI simulated stereopairs, using OEEPE ground control data and different number of control points.

Fig 5.4 - Plotting of residuals obtained for simulated OMI stereopairs (a) in E, N, and (b) in height, plan and 3D [UTM projection].
Better models are obtained with OMI data, due to the better pixel resolution of 5m. Models with 3D precision of 8.6m and 9.1m were obtained with 16 and 6 GCPs configurations, respectively. However, in these tests, the worst model was obtained with the 13 GCPs configuration. This is due to a worsening in plan, more specifically in East (UTM projection). This, again, may be explained by the distribution of the pseudo-errors in the image coordinates of the control. The residuals observed on the check points were randomly distributed.

5.3.3. Orientation of OPS simulated data

The accuracies obtained from orientating OPS simulated data are presented in table 5.3. Figures 5.6a and 5.6b show the residuals obtained in E and N, and in height, plan
and 3D, respectively. Larger residuals were also obtained in N than in E [UTM projection] for the OPS models.

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Table 5.3 - Residuals obtained orientating OPS simulated stereopairs, using OEEPE ground control data and different number of control points.

The models obtained with OPS data are very poor due to the very poor pixel ground resolution, approximately 18mx24m, and to the very low B/H=0.3. The latter is responsible for the very low precision obtained in height. For a 6 GCPs configuration, a 61m and 17m accuracy was achieved in height and in plan, respectively. Similar variations to those pointed out to the ASTER and OMI simulated models occur, showing sometimes slightly better models being obtained with fewer control. These variations are very small relative to the precisions found.

However, there is no direct explanation for the very small residual obtained in height for the 16 GCPs configuration model. The model was orientated excluding the weight matrix Q [§3.2.6] for the measurements, or errors of the control, with worse precisions being obtained. For this case, residuals of 59.6m and 16.9m were obtained in height and in plan using the same control. These results lead to the conclusion that the control used in the 16 GCPs configuration was very good. Data extracted from worse control had a very low weight and was almost ignored in the computations in favour of the better control. This result shows how important weighting the control may be for the model orientation.
Fig 5.6 - Plotting of residuals obtained for simulated OPS stereopairs (a) in E, N, and (b) in height, plan and 3D [UTM projection].

Fig 5.7 - Plotting of the residuals (a) in plan and (b) in height for 106 check points, of an OPS model orientated using the LAI orientation program.
A sketch of the residuals obtained in 106 check points after orientation of the model using 12 GCPS is presented for plan and height in figures 5.7a and 5.7b, respectively. A random distribution of these residuals is observed over the model, showing the effectiveness of the orientation.

5.3.4. Accuracies expected for the ASTER, OMI and OPS sensors

The accuracies of the ASTER, OMI and OPS simulated models are plotted in height, plan and 3D in figures 5.8 to 5.10, respectively. Accuracies of 32m, 9m and 63m were obtained in 3D for the ASTER, OMI and OPS sensors, respectively. These results obtained with simulated data are assumed accurate to 10%, according to the data validation performed in chapter 4.

An accuracy of 26m in height and of 19m in plan should be expected for an ASTER model orientated with 6 GCPs well distributed in an area covering approximately 60kmx240km. For the OMI sensor, accuracies of 8m and of 4.5m should be expected in height and in plan, respectively, for a 6 GCPs configuration. The accuracy of an OPS model also orientated with 6 GCPs should be expected to be 61m in height and of 17m in plan.

The intervals of precision given to the forecast accuracies of the future ASTER, OMI and OPS models, were extrapolated from the data validation carried out with SPOT real and simulated data [§4.4]. Larger errors may be encountered with real ALTI models, and larger intervals of precision may be assumed.

Additionally, other factors must be considered. During several years of tests with SPOT data, several research centres have claimed very different accuracies at times [Dowman et al., 1991]. The same research centres have also sometimes presented very different model accuracies for SPOT models, obtained with SPOT data taken at different times, or covering different areas [Gugan and Dowman, 1988a; Gugan and Dowman, 1988b]. The accuracy of the model depends on several factors, such as the modelling approach, the type and characteristics of the data and of the control used for the orientation.
Of the tests carried out with simulated ALTI, the OMI sensor is the sensor producing the best models. This is mainly due to its better pixel resolution of 5m, against 15m and approximately 20m for the ASTER and OPS sensors, respectively. The precisions of the models are approximately proportional to their respective pixel resolution. However, in spite of the very small difference of pixel resolution of the ASTER and the OPS sensors, OPS gives comparatively poorer results. The differences in plan between models of these two sensors are very similar [Fig 5.9]. The large difference of residuals observed in 3D [Fig 5.10] is mainly due to the differences registered in height [Fig 5.8]. These differences may be justified by the difference in B/H of the models. The OPS models have a B/H=0.3 while the B/H of the ASTER models is approximately 0.6. The OMI models also have a B/H=0.7, higher than any of the other two models, which also contributes to better accuracies in height.

Fig 5.8 - Plotting of residuals obtained for simulated ASTER, OMI and OPS in height [UTM projection].
Chapter 5. Orientation of SPOT, ASTER, OMI and OPS simulated data

Fig 5.9 - Plotting of residuals obtained for simulated ASTER, OMI and OPS in plan [UTM projection].

Fig 5.10 - Plotting of residuals obtained for simulated ASTER, OMI and OPS in 3D.
5.4. Comparison between SPOT and ASTER, OMI and OPS models

5.4.1. Introduction

The SPOT-like sensors were simulated as described in §4.1.2 with the same ground data used for the simulation of the ALTI [§5.2]. These theoretical sensors have characteristics identical to those of SPOT, but with along track angles similar to those of ASTER, OMI and OPS. A comparison is made between the SPOT-like and SPOT models. Relating the ALTI models with SPOT-like models allows a further comparison of these with SPOT.

The orientation process and the initial data used for these tests are also similar to that previously used testing the simulated ASTER, OMI and OPS data.

5.4.2. Orientation of SPOT-ASTER simulated data

The simulated SPOT-ASTER model presented the accuracies given in table 5.4. The results are given in meters, in UTM projection, and are plotted in figures 5.11a and 5.11b. A best model was obtained using 16 GCPs, with 14.6m and 9.9m accuracy in height and in plan, respectively. An accuracy of 16.6m in height and 10.8m in plan was obtained with the 6 GCPs configuration.

<table>
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Table 5.4 - Residuals obtained orientating SPOT-ASTER simulated data.
Chapter 5. Orientation of SPOT, ASTER, OMI and OPS simulated data

A comparison between the results obtained for the SPOT-ASTER models [Table 5.4] and those obtained for ASTER [Table 5.1], shows that better models are obtained with SPOT-ASTER data. Since all the orbital and viewing characteristics are similar to both sensors, this is due to their different pixel resolution. The differences found correspond approximately to the difference in pixel resolution between the two sensors.

Residuals larger in E (East) than in N (North), [UTM projection] were also observed for the SPOT-ASTER models.

5.4.3. Orientation of SPOT-OMI simulated data

Table 5.5 shows the residuals obtained orientating the SPOT-OMI simulated data for several control configurations. The residuals in E and N are plotted in figure 5.12a, and in height, plan and 3D in figure 5.12b. An accuracy of 11.4m in height and 9.4m in plan was obtained with a 6 GCPs configuration.
Chapter 5. Orientation of SPOT, ASTER, OMI and OPS simulated data

The simulated OMI models give smaller residuals than the SPOT-OMI simulated data sets. This is observed by comparison of tables 5.2 and 5.5. Similarly to what was previously stated for ASTER and for SPOT-ASTER data, these results are justified by the different pixel resolution of OMI and the theoretical SPOT-OMI sensor.

<table>
<thead>
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Table 5.5 - Residuals obtained orientating SPOT-OMI simulated data.

[Fig 5.12a] [Fig 5.12b]

Fig 5.12 - Plotting of residuals obtained for simulated SPOT-OMI data (a) in E, N, and (b) in height, plan and 3D [UTM projection].
5.4.4. Orientation of SPOT-OPS simulated data

The accuracies obtained for SPOT-OPS models are presented in Table 5.6. The results are given in the UTM projection, and are plotted in Figs 5.13a and 5.13b. A best model was obtained using 16 GCPs, with a 29.6m and 8.7m accuracy in height and plan respectively. An accuracy of 33.4m in height and 10.8m in plan was obtained for the 6 GCPs configuration.

<table>
<thead>
<tr>
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<td>33.4</td>
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</tr>
</tbody>
</table>

Table 5.6 - Residuals obtained orientating SPOT-OPS simulated data.

![Fig 5.13a](image1.png)  ![Fig 5.13b](image2.png)

Fig 5.13 - Plotting of residuals obtained for simulated SPOT-OPS data (a) in E, N, and (b) in height, plan and 3D [UTM projection].
In this case, the differences of accuracy found for the OPS [Table 5.3] and for SPOT-OPS [Table 5.6] are also proportional to the difference between their pixel resolutions.

5.4.5. Comparison between the accuracies achieved by SPOT-like models, and by ASTER, OMI and OPS simulated models

The residuals obtained with the simulated ASTER, OMI and OPS data and SPOT-like data are plotted on figures 5.14, 5.15 and 5.16, in height, plan and 3D, respectively. In each case, the results obtained for the ASTER, OMI and OPS sensors are designated by (a), while the plots showing the residuals obtained orientating the SPOT-like models are designated by (b).

The analysis of the tests performed shows a relation between the residuals obtained and the pixel resolution of the three ALTI sensors tested and their respective theoretical SPOT-like sensors. An along track sensor with a pixel resolution $n$ times larger than another along track sensor with similar viewing and geometric characteristics, gives models approximately $n$ times poorer.

The analysis of figures 5.14 and 5.15 show that the ASTER, OMI and OPS models differ from their corresponding SPOT-like models. The SPOT-like models have very similar residuals in plan for the three different data sets [Fig 5.15b]. Conversely, the residuals in plan for the ASTER, OMI and OPS data are very different for the three sensors [Fig 5.14a]. This occurrence is due to the dependency of the accuracy on the pixel resolution of each sensor.

The same justification does not apply to the different residuals obtained in height. Although the pixel resolution is 10m for all SPOT-like sensors, the residuals obtained are not similar. Large differences are observed for the different SPOT-like models tested. The three simulated SPOT-like sensors have all similar characteristics, but the viewing angles [table 4.3]. The B/H of the theoretical SPOT-ASTER, SPOT-OMI and SPOT-OPS are 0.6, 0.7 and 0.3, respectively. Figure 5.14b shows that larger residuals are observed for models with smaller B/H.

The combined effect of the B/H and the pixel resolution of the sensors thus justify the larger residuals were obtained for the SPOT-OPS and the smaller for the SPOT-OMI models [Fig 5.16].
Chapter 5. Orientation of SPOT, ASTER, OMI and OPS simulated data

Fig 5.14 - Plotting of residuals obtained in height for simulated (a) ASTER, OMI and OPS sensors, and (b) for SPOT-like data.

Fig 5.15 - Plotting of residuals obtained in plan for simulated (a) ASTER, OMI and OPS sensors, and (b) for SPOT-like data.
5.4.6. Comparison between the accuracies achieved by SPOT models, and by ASTER, OMI and OPS simulated models

In figure 5.17 is a plot of (a) the residuals in height and (b) in plan obtained orientating real SPOT data and simulated SPOT-like models. All the sensors have approximately 10m pixel resolution. The SPOT model has across track angles of 20.5°L and 22.3°R, and B/H=0.75 [Dowman et al., 1991].

It was previously observed in §5.4.5, that the planimetric accuracy of the model depends on the pixel resolution of the sensor. All the SPOT-like sensors and the SPOT sensor have similar pixel resolution of 10m, and the models show almost similar planimetric accuracies [Fig 5.17b]. The ASTER, OMI and OPS sensors have different pixel resolution, directly affecting the planimetric accuracy: sensors with larger pixel resolutions give poorer models [Fig 5.18b].
Chapter 5. Orientation of SPOT, ASTER, OMI and OPS simulated data

Fig 5.17 - Plotting of residuals obtained for the SPOT OEEPE test data and the simulated SPOT-like sensors (a) in height, and (b) in plan.

Fig 5.18 - Plotting of residuals obtained for the SPOT OEEPE test data and the simulated ASTER, OMI and OPS sensors (a) in height, and (b) in plan.
It was also concluded in §5.4.5 that the accuracies obtained in height for ALTI were directly related to the B/H of the models. In spite of the almost similar B/H and similar pixel resolutions, SPOT data gives better models in height than SPOT-OMI [Fig 5.17a]. The observed differences may only be justified by the fact that SPOT is an ACTI sensor while SPOT-OMI is an ALTI sensor, because all the other characteristics are similar to both sensors. This explains the similar accuracies obtained in height for the SPOT and for OMI data [Fig 5.18a], although the pixel resolution of the SPOT sensor is approximately twice larger than that for the OMI sensor.

The SPOT-OMI data was simulated assuming a sensor with the same physical characteristics of the SPOT sensor, but with along track angles similar to those of OMI. The SPOT and the SPOT-OMI simulated models considered on the tests have both similar B/H~0.7. Hence, a comparison between these two types of models give the accuracy that can be expected for a SPOT sensor if equipped with an along track viewing system. Future along track data extracted from a SPOT sensor, may be expected to achieve an accuracy of 11.4m in height and of 9.4m in plan using 6 GCPs. For a similar control configuration, an across track SPOT model will have accuracies of 6.0m and of 12.9m in height and plan, respectively.

Generally, it was found that the simulated SPOT along track models will have a height accuracy twice worse than that of the across track models, while the accuracy in plan will be approximately similar. Therefore, the adoption of along track capability to the SPOT sensor, keeping its present physical characteristics, will not be advantageous. It should only be adopted if other characteristics of the along track sensors are proved to be necessary and advantageous to the market, or if its ground resolution is improved to at least half of the actual values.

In summary, both ASTER and OPS are expected to give worse results than SPOT data. OMI is expected to give the same order of accuracy in height while being approximately twice as precise in plan than SPOT [Fig 5.18]. Along track models obtained from SPOT will be worse than the existing across track SPOT data.
5.5. The effect of off-set on OMI simulated models

5.5.1. Effect of off-set on overlapping of OMI stereo imagery

An offset in across track was introduced to the OMI sensor [§4.1.2], to increase the overlap of the stereopair [Chaloner, 1992].

The backward looking sensor views the same points on the ground approximately 92 sec after they have been imaged by the forward looking sensor. During that interval, the Earth rotates Eastwards and the two images do not completely overlap. From studying OMI simulated data with no off-set, it was observed that a 50% to 60% overlap was obtained [Fig 5.19a]. A 90% overlap was observed when a ±1° off-set was introduced in the across track direction [Fig 5.19b].

Chaloner [1992] did not specify the off-set angle to be adopted on the OMI viewing system. However, he mentioned that this would be chosen such that a 90% overlap would be achieved. The ±1° off-set used during the simulation of OMI data gives approximately the required 90% overlap and was thus adopted for all subsequent simulations on OMI data. However, it is important to study how different the results would be if no off-set had been considered.

Fig 5.19 - Sketch of overlap of OMI simulated images (a) without, and (b) with ±1° across track offset.
5.5.2. Test of effect of off-set on OMI models

If no off-set is introduced, the overlap decreases to about 50% and two options arise for the choice of ground control. Either the ground control is chosen to fall entirely within the overlapping zone, or monoscopic control is considered. For comparison with the results obtained in section §5.3.2, the same number of ground control points is used per image and approximately the same control configuration was kept [Fig 5.1].

The results obtained are presented in table 5.7 and the residuals are plotted in figure 5.20 (a) in height and (b) in plan.

<table>
<thead>
<tr>
<th>nGCPs</th>
<th>OMI ±1°offset</th>
<th>OMI no offset</th>
<th>OMI no offset + mono GCPs</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>H</td>
<td>2D</td>
<td>3D</td>
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Table 5.7 - Residuals obtained orientating simulated OMI data with or without off-set, and with or without monoscopic GCPs.
Chapter 5. Orientation of SPOT, ASTER, OMI and OPS simulated data

5.5.3. Analysis

Although the planimetric accuracies are very similar for all the tested models, significant differences are observed in height. The best models are achieved with the 90% overlapping data, built with ±1° offset. The models with no offset and a 50% to 60% overlap have smaller residuals when monoscopic GCPs are considered. Although the OMI model orientated using only stereoscopic GCPs may be well-distributed over the overlapping area, the monoscopic GCPs additionally contribute to a better distribution over each image of the stereomodel, hence towards a better orientation of the model.

However, although the use of monoscopic GCPs may produce a better orientation, the residuals are still larger than the residuals of models with ±1° offset. The difference encountered may be as large as 22%, and is thus large enough to justify the adoption of the offset.

![Graph showing residuals](Fig 5.20a)

![Graph showing residuals](Fig 5.20b)

Fig 5.20 - Residuals obtained with simulated OMI models with no off-set; with no off-set and using monoscopic GCPs; and with ±1° off-set (a) in height, and (b) in plan.
5.6. Orientation of multiple linear array imagery

5.6.1. Introduction

The LAI program was developed to orientate simultaneously several images taken during the same orbit and up to three different orbits. This allows the orientation of blocks of LAI. To test this feature of the program, multiple SPOT and OMI stereo imagery was simulated covering the OEEPE test area [§4.1.3].

This test also examines the theoretical improvement of the model if more images are used [Welch, 1980; Kratky, 1988].

5.6.2. Orientation of multiple SPOT data

Data was simulated for this test with the characteristics of the real SPOT data used for the OEEPE test [§4.1]. The stereopair used is formed by two sets of data simulated with viewing angles 20.5°L and 22.3°R. The three image model was formed by addition of an extra set of vertical looking simulated SPOT data to the stereopair. The results of the orientations performed are presented in table 5.8, and plotted in height and in plan in figures 5.21a and 5.21b, respectively.

<table>
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<th>rms (m) with three image SPOT model</th>
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<td>16.6</td>
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</tbody>
</table>

Table 5.8. Residuals obtained for a stereopair and a three image model of SPOT simulated imagery.
Chapter 5. Orientation of SPOT, ASTER, OMI and OPS simulated data

Fig 5.21 - Residuals obtained for a stereopair and a three image model of simulated SPOT imagery (a) in height, and (b) in plan.

The differences in height and in plan between a stereopair and a three image model are very small. The average improvement is approximately 8% in 3D. Additionally, considering that the residuals have a 10% confidence, the differences encountered are below the confidence value of the results and the theoretical improvement registered is not significant.

5.6.3. Orientation of multiple OMI data

A vertical looking OMI image was simulated and added to the stereomodel previously used [§5.3.2] to form a three image model. Two additional images with backward and forward looking angles of 10° were also simulated to form the five images stereomodel. The residuals obtained from the orientation of the three different models are given in table 5.9 and plotted in height and in plan in figure 5.22.
Table 5.9 - Residuals obtained for stereomodels of 2, 3 and 5 OMI simulated images.

When a third image was introduced to the stereomodel, an improvement of about 14% was observed. This is above the 10% interval of confidence and it may be considered significant. The use of five images, however, did not give a significant improvement to the results, relative to the three image model. The use of a third image stabilises the model and improves the accuracy in plan and in height.

![Fig 5.22a](image1)

![Fig 5.22b](image2)

Fig 5.22 - Residuals obtained for stereomodels of 2, 3 and 5 OMI simulated images (a) in height, and (b) in plan.
5.6.4. Summary of results

The results of the tests carried out with multiple SPOT stereo imagery showed that a three image model has no advantages relative to a SPOT stereopair. The improvement registered was approximately 8%, which is inferior to the 10% confidence obtained during data validation for simulated data.

An improvement of approximately 14% was observed to the three image model of OMI data, which was considered significant. The five image stereomodel does not improve the model significantly relative to the three image model.

Summarising, the use of an additional third image to an across track stereopair does not improve the accuracy of the model. However, adding a third image to an along track stereopair may significantly improve the model.

5.7. Orientation of hybrid models of LAI

5.7.1. Introduction to test

This test was performed with simulated OMI, SPOT and ASTER data, covering the OEEPE test area. In this case, however, the data was mixed in order to forecast the accuracy of hybrid stereo models such as OMI+SPOT and OMI+ASTER. This test will also show the capability of the LAI program to orientate stereomodels obtained by combination of along track and across track imagery.

5.7.2. Orientation of combined OMI and SPOT simulated data

One OMI image with along track angle 20° and one SPOT image with across track angle 22.3° were used to form the hybrid OMI+SPOT model referred to in table 5.10. The accuracy of an OMI stereomodel [§5.3.2] and of a SPOT stereomodel [§4.4.3] are also presented on table 5.10 for comparison purposes. The residuals obtained in height and in plan are plotted on figures 5.23a and 5.23b, respectively.
Table 5.10 - Residuals obtained for OMI, SPOT and combined OMI+SPOT imagery models.

Figure 5.23b shows that the planimetric accuracy of the hybrid model is less accurate than that of an OMI stereomodel and more accurate than that of a SPOT stereomodel. However, the same relation is not verified in height. The hybrid model OMI+SPOT gives worse accuracies in height than any of the OMI or the SPOT stereomodels.

Fig 5.23 - Residuals obtained for OMI, SPOT and OMI+SPOT imagery models (a) in height, and (b) in plan.
5.7.3. Orientation of combined OMI and ASTER simulated data

A second test was carried out using a stereomodel composed of an OMI image with an along track angle of 20° and an ASTER image with an along track angle of 29.7°. The residuals obtained for the OMI+ASTER hybrid model are presented in Table 5.11, along with the results obtained for an OMI and an ASTER stereomodels. The residuals obtained in height and in plan are plotted in Figures 5.24a and 5.24b, respectively.

<table>
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<th>rms (m) ASTER</th>
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Table 5.11 - Residuals obtained for OMI, ASTER and combined OMI+ASTER imagery models.

The residuals obtained in plan for the OMI+ASTER model are larger than the residuals observed for the OMI stereomodel, and smaller than the residuals for the ASTER stereomodel. The residuals in height are also larger for the OMI+ASTER model than for the OMI stereomodel, and smaller than the residuals found for the ASTER stereomodel.
5.7.4. Summary of results

Two hybrid stereomodels were tested: OMI+SPOT and OMI+ASTER. The former corresponds to a model resulting from a combination of one ALTI and one ACTI, while the latter is a model formed of two ALTI. In both instances, the planimetric resolution of the hybrid models is worse than that of an OMI stereopair and better than either a SPOT or an ASTER stereopair. However, the accuracy in height for these models does not follow the same pattern.

For both OMI+SPOT and OMI+ASTER models, the accuracy in height is worse than that of an OMI stereopair. However, while the accuracy of an OMI+ASTER model is better than that of an ASTER stereopair, the height accuracy of an OMI+SPOT model is worse than that of a SPOT stereopair.

In summary, the planimetric accuracy of a hybrid model is expected to be worse than that of a stereopair of a sensor with best pixel resolution, and better than that of a
stereopair of a sensor with worst pixel resolution. The same relation is observed for the accuracy in height of an hybrid model formed from two along track viewing sensors. If the hybrid model is composed of one along track and one across track viewing sensors, worse accuracies than those of a stereopair of each of the considered sensors should be expected.

5.8. Conclusions

Tests were performed with ASTER, OMI and OPS simulated data, in order to forecast the accuracy of the models to form from these future sensors data. For a 6 GCPs configuration, planimetric accuracies of 19m, 4.5m and 17m should be expected to be achieved from the ASTER, OMI and OPS models, respectively. The height accuracies expected for the same sensors should be 26m, 8m and 61m, respectively. These results are in agreement with tests independently carried out by Shimada et al. [1992] with real OPS data.

A test area of 21kmx25km in Mt. Akagi, 100km north west of Tokyo, was oriented, with errors with a standard deviation of 59.08m computed for 100 GCPs relative to a DTM of the same region published by the Japan Geographic Agency (JGA). Shimada et al. [1992] mention that an error of DTM derivation using OPS' stereo bands is less than 80m. It is also mentioned that more tests will be necessary to conclude more accurately which is the accuracy achievable by OPS stereo data.

Both ASTER and OPS are expected to give worse models than SPOT data, while OMI is expected to give the same order of accuracy in height while being approximately twice as precise in plan than SPOT models are.

With reference to the tests carried out with OMI data, an across track offsets of ±1° were considered, in order to ensure a 90% overlap of the stereopair. A study with simulated data showed that the offset improved the results as much as 22% compared with models with no offset, and 50% to 60% overlap.
The tests performed with SPOT-like data allowed the comparison of ALTI with ACTI. The SPOT-like models were used as an intermediate stage between the ASTER, OMI and OPS, and the SPOT models. It was verified that the pixel resolution of the sensor has a direct influence on the planimetric accuracy of the models. Sensors with poorer pixel resolution give poorer models. The accuracies obtained in height also depend on the B/H of the model. This subject will be studied separately in chapter 6.

Additional tests carried out on orientating multiple LAI showed that, within the 10% confidence of the results, the addition of a third image to an across track stereopair does not improve the accuracy of the model. However, an additional image added to an along track stereopair results in the model’s improvement.

The LAI program was also tested for the orientation of hybrid models, i.e., stereomodels resulting from the combination of different LAI, which were studied for two different cases. In the first, one ALTI and one ACTI were combined to form a hybrid stereomodel. In the second, two ALTI with different pixel resolutions were combined to form another stereomodel. The planimetric accuracy of a hybrid model is expected to be worse than that of a stereopair for a sensor with best pixel resolution, and better than that of a stereopair for a sensor with worse pixel resolution. The same relation is verified for the accuracy in height of a hybrid model formed from two along track viewing sensors. However, if the hybrid model is formed from one along track and one across track viewing sensors, worse accuracies than those found from any stereopair of each of the considered sensors should be expected.
Chapter 5. Orientation of SPOT, ASTER, OMI and OPS simulated data
Chapter 6.

Influence of data characteristics on model orientation

6.1. Introduction

The data to use in the tests was simulated for each case considering the characteristics to examine. Other characteristics may depend on the user. These include the accuracy to which the ground coordinates of the control are known, the errors of identification and measurement of the control on the image, and the control configuration.

The characteristics of the model and the type of data used for each orientation has major influence on the accuracy. Some of the model characteristics, such as the B/H, the continuity or not of the data, and the strip length are variable from model to model. Variations of these characteristics affect the model orientation. Therefore, those relations are tested and analysed in this chapter.

The first factor to be tested is the accuracy of the control, since this suffers directly influenced by the user. Additionally, the errors added to the control during the simulation process are the most difficult to choose and to control, also due to a lack of references on the subject.

Some tests were also performed to study the effect of the attitude data on the orientation process. This study was made with OMI data, using very few control points, and different types of attitude data. Some tests were performed using only relative attitude data, while others assumed the knowledge of absolute attitude data.
Chapter 6. Influence of data characteristics on model orientation

The influence of the control distribution over the model, the effect of using or not GCPs at the same height for the model orientation, and the orientation of non-continuous LAI are also tested in this chapter.

6.2. Choice of sensor and data for the tests

One from ASTER, OMI or OPS sensors should be adopted for the tests, since they represent future ALTI from satellite platforms. According to the tests performed with simulated data in chapter 5, the OMI sensor is the ALTI sensor to give the best models. Therefore, OMI simulated data was adopted for the tests, instead of ASTER and OPS. The OMI data was simulated as described in §5.2 and the control configuration sketched in figure 6.1 was used in most tests. Simulated SPOT data was used in similar tests as representative of ACTI and similar control configurations were adopted. The usual strip considered is 110km long for all the tests, unless specified otherwise. Any changes on the data used or procedure, in order to satisfy the test requirements, will be stated for each test.

![Fig 6.1 - Control configurations adopted for the tests.](image)
6.3. Influence of simulated error on control

6.3.1. Introduction

During the simulation process, random errors simulating errors of identification and measurement of the control are added to the ground and to the image coordinates. The errors added to the ground coordinates simulate errors incurred during point extraction from maps, aerial photography or other sources. The errors added to the image coordinates simulate possible errors of interpretation of the imagery and of measurement. These are variable and may be defined by the user during the simulation process [§4.3].

A study was made in §4.3 to check which type of errors should be added to the image coordinates. The method used resulted from a comparison between the errors described by two authors [Rodriguez et al., 1988; Gugan, 1991], the only references found. The errors finally added to the simulated image coordinates were in accordance with Gugan [1991]. However, if better quality imagery is used, these may be smaller, or vice-versa. Therefore, a study is made on how the model accuracy may vary if there is a variation of the quality of the control used. The same principle may be applied to the quality of the control ground coordinates. The effect of changes in the precision of the ground coordinates to the model accuracy is also assessed.

6.3.2. Accuracy of an error-free model.

Prior to the tests, the accuracy of an error-free ALTI model was tested. The OMI simulated data was orientated using the control configurations given in figure 6.1, and error-free image and ground coordinates. The results from this test are given in table 6.1, and plotted in figure 6.2.
Chapter 6. Influence of data characteristics on model orientation

<table>
<thead>
<tr>
<th>number</th>
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Table 6.1 - Residuals obtained for OMI stereomodel with error-free simulation of both the image and ground coordinates.

Fig 6.2 - Residuals obtained for OMI stereomodel with error-free simulation of both the image and ground coordinates.

The residuals obtained result from the approximations made during the orientation process and during the computation of the ground coordinates of the check points. The
worse case occurs for the orientation using 4 control points, with 3D residual of 1.0m. These residuals are very small compared to the pixel resolution of the OMI sensor, which is 5m. An accuracy of half a pixel is usually assumed for the measurements on the image, which theoretically corresponds to approximately 2.5m. Hence, the residuals introduced to the orientation by approximations during the orientation of ALTI are negligible.

6.3.3. Effect of quality of image coordinates on model accuracy

To test the effect of the quality of the image coordinates of the control on the model accuracy, different sets of OMI data were simulated. The characteristics adopted for the test were similar to the previous test. However, simulated errors were added to the coordinates. The three different sets of data studied, had errors in the image coordinates with a distribution by classes [§4.3] shown in table 6.2.

<table>
<thead>
<tr>
<th>class of control</th>
<th>simulated error (%)</th>
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<tr>
<td></td>
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<tr>
<td>1</td>
<td>23.7</td>
</tr>
<tr>
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<td>16.8</td>
</tr>
<tr>
<td>5</td>
<td>11.0</td>
</tr>
</tbody>
</table>

Table 6.2 - Distribution of the control by classes, using different simulated errors ($\sigma$).

The accuracy of the models gets worse when worse quality control is used for the orientation [Fig 6.4]. This effect is more noticeable in height than in plan, as observed by comparing figures 6.3a and 6.3b. The simulated data with $\sigma=0.7$ will be considered for all the tests, since it gives the best approximation to the point identification observed with real data. However, the accuracy of a model may be improved if better control is used.
Chapter 6. Influence of data characteristics on model orientation

<table>
<thead>
<tr>
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<th>σ=0.7</th>
<th>σ=0.6</th>
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<td>H  2D  3D</td>
<td>H  2D  3D</td>
<td>H  2D  3D</td>
</tr>
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<td>GCPs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td>7.5 5.2  9.1</td>
<td>7.2 4.5  8.4</td>
<td>5.9 4.0  7.1</td>
</tr>
<tr>
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<td>7.8 5.4  9.5</td>
<td>7.4 4.5  8.7</td>
<td>6.0 4.2  7.3</td>
</tr>
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<td>5.9 4.1  7.2</td>
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<td>6.3 4.5  7.7</td>
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<tr>
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<td>9.5 5.9 11.2</td>
<td>8.0 5.4  9.6</td>
<td>7.3 5.0  8.8</td>
</tr>
</tbody>
</table>

Table 6.3 - Residuals obtained for OMI stereomodels with different errors affecting the image coordinates.

Fig 6.3 - Residuals obtained for OMI stereomodels with different errors affecting the image coordinates (a) in height, and (b) in plan.
Chapter 6. Influence of data characteristics on model orientation

6.3.4. Effect of quality of ground coordinates on model accuracy

To study the effect of the accuracy of the ground control on the model orientation, simulated OMI data was orientated for two cases. First, error-free ground coordinates were used. Second, an orientation was performed adding random errors to the control ground coordinates with standard deviation of 3m in height and of 3m in plan. The accuracy of the models after orientation is shown in table 6.4 and presented graphically in figures 6.5 and 6.6.

The differences encountered between the accuracies of the error-free models and the models affected by errors of 3m both in height and in plan are very small. For most cases, they are smaller than 1m, in height, in plan and in 3D. While the accuracy of the control is smaller than the pixel resolution, the model accuracy is not much affected by the errors in the ground control.
Chapter 6. Influence of data characteristics on model orientation

<table>
<thead>
<tr>
<th>number</th>
<th>( \sigma_H=0 \text{m}; \sigma_{2D}=0 \text{m} )</th>
<th>( \sigma_H=3 \text{m}; \sigma_{2D}=3 \text{m} )</th>
</tr>
</thead>
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<tr>
<td></td>
<td>H</td>
<td>2D</td>
</tr>
<tr>
<td>GCPs</td>
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<td></td>
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<tr>
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<td>6.8</td>
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<td>4.5</td>
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<td>4.6</td>
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<td>7.3</td>
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</tr>
</tbody>
</table>

Table 6.4 - Residuals obtained for OMI stereomodels with \( \sigma=0.7 \) for image coordinates error and different errors affecting the ground coordinates.

[Fig 6.5a]  [Fig 6.5b]

Fig 6.5 - Residuals obtained for OMI stereomodels, with \( \sigma=0.7 \) for image coordinates error and different errors affecting the ground coordinates, (a) in height, and (b) in plan.
Chapter 6. Influence of data characteristics on model orientation

6.3.5. Effect of large errors of ground coordinates on model accuracy

In two drastic tests, the ground coordinates of the control were cut to the nearest fifty meters and another to the nearest hundred meters. The residuals of orientating the OMI data with such errors on the ground coordinates of the control are presented in table 6.5.

<table>
<thead>
<tr>
<th>number of control points</th>
<th>( \sigma_{3D}=50\text{m} )</th>
<th>( \sigma_{3D}=100\text{m} )</th>
</tr>
</thead>
<tbody>
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<td>GCPs</td>
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<td>H 2D 3D</td>
</tr>
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<td>16.7 24.2 29.5</td>
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</tr>
<tr>
<td>13</td>
<td>17.2 23.9 29.4</td>
<td>27.1 31.9 41.8</td>
</tr>
<tr>
<td>11</td>
<td>16.9 24.6 29.3</td>
<td>27.5 34.2 43.9</td>
</tr>
<tr>
<td>8</td>
<td>17.1 25.2 30.5</td>
<td>28.4 35.5 45.4</td>
</tr>
<tr>
<td>6</td>
<td>17.3 26.0 31.2</td>
<td>31.6 37.8 49.3</td>
</tr>
<tr>
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<td>18.4 27.2 32.8</td>
<td>35.2 39.8 53.1</td>
</tr>
</tbody>
</table>

Table 6.5 - Residuals obtained for OMI stereomodels orientated with gross errors on the ground coordinates of the control.
The image coordinates of the control was still simulated for $\sigma=0.7$, and the check points were affected by errors of $\sigma_H=3m$ and $\sigma_{2D}=3m$.

The models orientated using ground coordinates with very small precision still give smaller residuals than the precision of the ground control. This was not verified when very accurate control was used for the orientation.

6.3.6. Summary of results

The accuracy of the model orientation depends on the quality of the control used. The quality of the image coordinates of the control has a different effect from that of the ground coordinates.

Worse quality of the image coordinates produces significative variations in the accuracy of the model. These variations are larger in height than in plan. On the other hand, variations on the precision of the ground coordinates of the control do not affect so strongly the accuracy of the model.

A comparison of the residuals presented in table 6.3 and table 6.4, shows the higher influence on the orientation of the quality of the identification of the control on the imagery than of the ground coordinates.

6.4. Influence of strip length

6.4.1. Introduction

The longer the strip of data to orientate, the longer is the time of acquisition of the data. Therefore, the variations of the orientation parameters are larger, and an orientation with similar number of control points gives more time-distant information. Hence, it might be reasonable to think that a worsening in the model orientation would be registered if the same number of control is used for the orientation. However, tests
carried out with SPOT data revealed that the accuracy would not change considerably for strips 60km to 240km long [Neto, 1989]. Due to the non-availability of data, it was impossible to test for longer strips of data.

OMI and SPOT data were simulated for very long strips, and orientated with control configurations as close as possible to the control configurations in figure 6.1. For the 3000km long strip, the Mediterranean Sea is covered and control lying on this region was rejected [§4.1.4]. However, the control configurations used were kept as close as possible to those of figure 6.1. The orientation of the strips was checked using approximately 360 check points.

6.4.2. Orientation of OMI models for different strip lengths

Three strips of OMI data of different lengths were simulated. The first strip is 110km long, the second is approximately 1500km and the third 3000km long. The accuracy of the orientated models are presented in table 6.5 and in figures 6.7 and 6.8.

<table>
<thead>
<tr>
<th>number</th>
<th>GCPs</th>
<th>strip length= 110km</th>
<th>strip length= 1500km</th>
<th>strip length= 3000km</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>H  2D  3D</td>
<td>H  2D  3D</td>
<td>H  2D  3D</td>
</tr>
<tr>
<td>16</td>
<td>16</td>
<td>7.2  4.5  8.4</td>
<td>7.6  4.6  8.9</td>
<td>8.0  4.9  9.4</td>
</tr>
<tr>
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<td>13</td>
<td>7.4  4.5  8.7</td>
<td>7.7  4.8  9.1</td>
<td>7.8  5.2  9.4</td>
</tr>
<tr>
<td>11</td>
<td>11</td>
<td>7.6  4.8  9.0</td>
<td>7.9  5.3  9.5</td>
<td>7.9  5.7  9.7</td>
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<td>8.0  5.5  9.7</td>
<td>8.3  5.6  10.0</td>
</tr>
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<td>6</td>
<td>6</td>
<td>7.9  5.2  9.5</td>
<td>8.0  5.6  9.8</td>
<td>8.1  5.5  10.4</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>8.0  5.4  9.6</td>
<td>8.2  6.2  10.2</td>
<td>8.9  5.8  11.2</td>
</tr>
</tbody>
</table>

Table 6.6 - Residuals obtained for OMI stereomodels with different strip lengths.
Chapter 6. Influence of data characteristics on model orientation

Fig 6.7 - Residuals obtained for OMI stereomodels with different strip lengths (a) in height, and (b) in plan.

Fig 6.8 - Residuals obtained in 3D for OMI stereomodels with different strip lengths.
The results show a very small difference in the residuals for the various strip lengths tested, either in height, in plan or in 3D. Although the differences obtained in height and in plan are not very visible for the three different strips in figure 6.7a and 6.7b, the analysis of table 6.5 shows larger differences occurring in height than in plan.

For a 4 control points configuration, accuracies of 8.0m and of 8.9m were registered in height for strips 110km and 3000km long, respectively. For the same strips, the accuracy in plan varied from 5.4m to 5.8m. Similar differences are found when comparing the accuracies obtained from orientating the same two strips for the other control configurations. However, these differences are so small, that they are not significant enough for further conclusions.

6.4.3. Orientation of SPOT models for different strip lengths

The residuals obtained from orientating three SPOT simulated strips are presented in table 6.6. The same residuals are plotted in Figures 6.9 and 6.10.

<table>
<thead>
<tr>
<th>number of GCPs</th>
<th>strip length= 110km</th>
<th>strip length= 1500km</th>
<th>strip length= 3000km</th>
</tr>
</thead>
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<td></td>
<td>H 2D 3D</td>
<td>H 2D 3D</td>
<td>H 2D 3D</td>
</tr>
<tr>
<td>16</td>
<td>6.2 11.2 12.8</td>
<td>6.7 11.8 13.6</td>
<td>7.2 11.7 13.7</td>
</tr>
<tr>
<td>13</td>
<td>6.9 12.7 14.4</td>
<td>7.5 12.1 14.2</td>
<td>7.7 13.4 15.4</td>
</tr>
<tr>
<td>11</td>
<td>6.6 12.5 14.1</td>
<td>8.4 12.7 15.2</td>
<td>8.5 13.8 16.2</td>
</tr>
<tr>
<td>8</td>
<td>7.0 13.2 14.9</td>
<td>8.3 17.2 19.1</td>
<td>8.9 16.4 18.6</td>
</tr>
<tr>
<td>6</td>
<td>7.2 15.9 17.4</td>
<td>8.7 16.9 19.0</td>
<td>9.4 17.0 19.4</td>
</tr>
</tbody>
</table>

Table 6.7 - Residuals obtained for SPOT stereomodels with different strip lengths.
Chapter 6. Influence of data characteristics on model orientation

Fig 6.9 - Residuals obtained for SPOT stereomodels with different strip lengths (a) in height, and (b) in plan.

Fig 6.10 - Residuals obtained in 3D for SPOT stereomodels with different strip lengths.
The orientations of the various strips have almost similar accuracies [Fig 6.10] when orientated with a large number of control points. For example, for a 16 GCPs configuration, a 3D accuracy of 12.8m was obtained for a strip 110km long, while a strip 3000km long orientated with a similar control configuration has an accuracy of 13.7m.

However, when a smaller number of control is used, the residuals increase both in height and in plan for the two longest strips [Figs 6.9a and b]. For example, for an 8 GCPs configuration the 3D accuracies of the 110km and the 3000km long strips are 14.9m and 18.6m, respectively.

6.4.4. Summary of results

Simulated OMI data covering areas 110km to 3000km long were orientated resulting models with very similar accuracies. However, the accuracy of SPOT models becomes significantly worse for longer strips, when a small number of control points is used. This effect became noticeable for model orientation with less than 13 GCPs, and strips as long as 1500km.

6.5. Influence of B/H of the model

6.5.1. Introduction

Variations in the B/H of the model are supposed to affect the model accuracy. Most authors refer to the relationship between the B/H of the stereomodel and the accuracy in height [Swann et al., 1987; Dowman et al., 1991]. The relationship was verified for SPOT models, but was never tested on ALTI. In this section, this is tested with both OMI and SPOT simulated data. The various B/H ratios tested were formed with angles as specified in table 6.7. These are forwards/backwards for OMI and right/left for SPOT.
Chapter 6. Influence of data characteristics on model orientation

<table>
<thead>
<tr>
<th>B/H</th>
<th>1.0</th>
<th>0.8</th>
<th>0.7</th>
<th>0.6</th>
<th>0.5</th>
<th>0.3</th>
</tr>
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<tbody>
<tr>
<td>B/F or R/L</td>
<td>±26°</td>
<td>±22°</td>
<td>±20°</td>
<td>±17°</td>
<td>±14°</td>
<td>±9°</td>
</tr>
</tbody>
</table>

Table 6.8 - Viewing angles considered for OMI and SPOT simulated models with various B/H.

6.5.2. Orientation of OMI models

The results of orientating the different OMI models with different B/H are presented in table 6.9, and plotted in figures 6.11 and 6.12.

<table>
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<th>B/H = 0.8</th>
<th></th>
<th>B/H = 0.7</th>
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<tbody>
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<td></td>
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<td>7.5</td>
<td>7.0</td>
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<td>4.0</td>
<td>7.6</td>
<td>7.1</td>
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<table>
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<td>H</td>
<td>2D</td>
<td>3D</td>
<td>H</td>
</tr>
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<td>12.7</td>
<td>19.5</td>
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</table>

Table 6.9 - Residuals obtained for OMI stereomodels with different B/H.
Chapter 6. Influence of data characteristics on model orientation

Fig 6.11 - Residuals obtained for OMI stereomodels with different B/H (a) in height, and (b) in plan.

Fig 6.12 - Residuals obtained in 3D for OMI stereomodels with different B/H.
Chapter 6. Influence of data characteristics on model orientation

For a 4 GCPs configuration, the 3D residuals obtained for models with B/H equal to 1.0 to 0.6 vary almost linearly from 8.6m to 10.6m, respectively, for a 4 GCPs configuration. However, although this variation is very small for these B/H, the models have large residuals for B/H of 0.5 and smaller.

6.5.3. Orientation of SPOT models

The accuracy of the SPOT simulated models with different B/H are presented in table 6.10 and plotted in figures 6.13 and 6.14.

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<td></td>
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<td></td>
<td>H 2D 3D</td>
<td></td>
<td>H 2D 3D</td>
</tr>
<tr>
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<td>16</td>
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<td></td>
<td>6.2 10.0 11.8</td>
<td></td>
<td>6.2 11.2 12.8</td>
</tr>
<tr>
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<td>13</td>
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<td>6.6 11.2 13.0</td>
<td></td>
<td>6.9 12.7 14.4</td>
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<td>6.6 11.9 13.3</td>
<td></td>
<td>6.5 12.0 13.6</td>
<td></td>
<td>6.6 12.5 14.1</td>
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<tr>
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<td>8</td>
<td>6.7 12.5 14.2</td>
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<td>7.0 12.4 14.2</td>
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<td>7.0 13.2 14.9</td>
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<td>6</td>
<td>6.9 14.9 16.4</td>
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<td>7.1 15.3 16.9</td>
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<table>
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<td></td>
<td>H 2D 3D</td>
<td></td>
<td>H 2D 3D</td>
</tr>
<tr>
<td>16</td>
<td>16</td>
<td>6.3 10.9 12.6</td>
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<td>6.9 11.3 13.2</td>
<td></td>
<td>7.8 12.2 14.4</td>
</tr>
<tr>
<td>13</td>
<td>13</td>
<td>6.8 11.9 13.7</td>
<td></td>
<td>7.9 11.8 14.2</td>
<td></td>
<td>8.5 13.2 15.7</td>
</tr>
<tr>
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<td>11</td>
<td>7.0 12.3 14.2</td>
<td></td>
<td>7.7 13.4 15.4</td>
<td></td>
<td>9.1 14.4 17.0</td>
</tr>
<tr>
<td>8</td>
<td>8</td>
<td>7.2 14.1 15.8</td>
<td></td>
<td>8.0 14.5 16.6</td>
<td></td>
<td>10.3 15.4 18.5</td>
</tr>
<tr>
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<td>6</td>
<td>7.6 16.0 17.7</td>
<td></td>
<td>8.5 17.2 19.2</td>
<td></td>
<td>13.4 19.2 23.4</td>
</tr>
</tbody>
</table>

Table 6.10 - Residuals obtained for SPOT stereomodels with different B/H.
Chapter 6. Influence of data characteristics on model orientation

Fig 6.13 - Residuals obtained for SPOT stereomodels with different B/H (a) in height, and (b) in plan.

Fig 6.14 - Residuals obtained in 3D for SPOT stereomodels with different B/H.
Chapter 6. Influence of data characteristics on model orientation

As expected, the models get worse for smaller B/H. The accuracies of the models do not vary significantly for B/H from 1.0 to 0.6, and when the variation occurs, it is more significant in height. For example, for a 6 GCPs configuration, the residual in height is 7.2m for a B/H=0.7, increasing to 13.4 for a B/H=0.3. The residuals obtained in plan are more stable than the residuals in height. For the same B/H of 0.7 and 0.3, the accuracy obtained in 2D is 15.9m and 19.2m, respectively. Hence, also using 4 GCPs, the accuracy in plan worsens by only 3.3m, while the accuracy in height suffers a variation of 6.2m.

6.5.4. Summary of results

The analysis of the results obtained from orientating SPOT and OMI stereomodels with varying viewing angles, and consequently various B/H, gave the following conclusions:

- The accuracy of the model decreases with the B/H. For models with B/H larger than 0.6, the orientation does not vary significantly. This was previously used in §5.3.4 to justify the low accuracy in height of the OPS simulated data (B/H=0.3).

- The variation of the height accuracy of the models is significantly more affected by the B/H of the model than the accuracy in plan. This was observed for SPOT and for OMI models, and can be observed by comparing figures 6.11a and 6.11b, to figures 6.13a and 6.13b.

- The B/H of the model for which the model accuracy gets significantly worse, is different for the SPOT and the OMI sensors. A SPOT stereopair with B/H=0.5 has still accuracy in height very similar to that of models with larger B/H, and it only gets worse for B/H smaller than 0.5. The accuracy in height of an OMI model deteriorates for B/H equal to 0.5. This result may be an effect from the type of sensor: ALTI or ACTI. ALTI models are more sensitive to the B/H of the model than ACTI.

200
6.6. Effect of symmetry of viewing angles

6.6.1. Introduction

The models used to test how the accuracy varies with the B/H of the model, had similar backwards and forwards angles for ALTI, and similar right and left looking angles for the case of ACTI. Tests were performed in this chapter, to study if these results are only a consequence of the B/H or if they are also influenced by the symmetry of the viewing angles.

When the viewing angles are not symmetrical, i.e., not similar in value, the pixel resolution, on the ground, is different for the two images. So is the pixel resolution of each image, and the precision to which a point can be identified on the image. Hence, different accuracies may be obtained for models with similar B/H, and with asymmetric viewing angles.

To test this hypothesis, OMI and SPOT models were simulated to form models with B/H=0.7, but with different viewing angles. A first case considers similar either backwards/forwards (OMI), or right/left for SPOT, ±20° looking angles. A second case was tested considering one angle of +30° and the other -7°. These angles were chosen such as to obtain a large asymmetry between the two viewing perspectives.

6.6.2. Effect on OMI data

The first model orientated in this test was formed with a 20° forwards and a 20° backwards looking angles images. The second was composed of a 30° forwards and a 7° backwards looking angles images. The residuals of the two models are presented in table 6.11 and are plotted in height, plan and 3D in figures 6.15 and 6.16.
Table 6.11 - Residuals obtained for OMI stereomodels with similar B/H but different angles.

<table>
<thead>
<tr>
<th>number of control pts</th>
<th>Symmetrical angles</th>
<th>Asymmetrical angles</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>H</td>
<td>2D</td>
</tr>
<tr>
<td>16</td>
<td>7.2</td>
<td>4.5</td>
</tr>
<tr>
<td>13</td>
<td>7.4</td>
<td>4.5</td>
</tr>
<tr>
<td>11</td>
<td>7.6</td>
<td>4.8</td>
</tr>
<tr>
<td>8</td>
<td>7.8</td>
<td>5.0</td>
</tr>
<tr>
<td>6</td>
<td>7.9</td>
<td>5.2</td>
</tr>
<tr>
<td>4</td>
<td>8.0</td>
<td>5.4</td>
</tr>
</tbody>
</table>

Fig 6.15 - Residuals obtained for OMI stereomodels with similar B/H and different viewing angles (a) in height, and (b) in plan.
The residuals obtained in height and in plan are almost similar for the two models. Although there is a very small tendency to smaller residuals in height by the model with asymmetrical viewing angles, this is too small to be considered significant. The larger difference encountered was registered for the maximum 16 GCPs configuration. An accuracy of 7.2m has achieved in height by the model with ±20° forwards/backwards looking angles, while a 6.2m was registered for the other model. The differences observed in plan for the two models are even smaller than those registered in height.

6.6.3. Effect on SPOT data

Table 6.12 shows the accuracies of the two SPOT models orientated for this test. The model with asymmetrical angles was formed with an image with a viewing angle of 7° to the right, and the other looking 30° to the left. The residuals are plotted in tables 6.17 and 6.18.
### Table 6.12 - Residuals obtained for SPOT stereomodels with similar B/H but different angles.

<table>
<thead>
<tr>
<th>number of control pts</th>
<th>Symmetrical angles</th>
<th>Asymmetrical angles</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>H</td>
<td>2D</td>
</tr>
<tr>
<td>16</td>
<td>6.2</td>
<td>11.2</td>
</tr>
<tr>
<td>13</td>
<td>6.9</td>
<td>12.7</td>
</tr>
<tr>
<td>11</td>
<td>6.6</td>
<td>12.5</td>
</tr>
<tr>
<td>8</td>
<td>7.0</td>
<td>13.2</td>
</tr>
<tr>
<td>6</td>
<td>7.2</td>
<td>15.9</td>
</tr>
</tbody>
</table>

Fig 6.17 - Residuals obtained for SPOT stereomodels with similar B/H and different viewing angles (a) in height, and (b) in plan.
Chapter 6. Influence of data characteristics on model orientation

For SPOT models with symmetrical viewing angles tend to be more precise in plan than the asymmetrical models. For the maximum number of ground control used, 16, accuracy in plan of 11.2m was registered for the model with symmetrical viewing angles, and 12.5m for the asymmetrical stereopair. This effect becomes negligible when a small number of ground control is adopted.

The height accuracy of the models does not vary much from symmetrical to asymmetrical image pairs, no matter the number of control used.

6.6.4. Summary of results

In general, the asymmetry in the viewing geometry of the images forming a stereomodel does not affect the accuracy of that model, if just a few ground control is used for the orientation, e.g., less than 8 GCPs.
Chapter 6. Influence of data characteristics on model orientation

The accuracy of OMI models tends to be affected in height, while SPOT models get worse in plan. However, the effect on OMI models is almost negligible. For the 16 GCPs configuration, the accuracy of the symmetric and asymmetric models suffers a maximum variation of 0.4m in 3D. The asymmetric SPOT models get worse about 1.3m relative to the symmetric model, for a similar 16 GCPs configuration.

6.7. Orientation of OMI models with very few control points

6.7.1. Introduction

The number of GCPs necessary for the orientation of LAI has been mentioned by several researchers as an important factor for the cost of map products [Swaan et al., 1987; O’Neill, 1991; Sharpe and Wiebe, 1991]. Several tests were performed to study the orientation of SPOT models with very few control points. Some research centres presented the results of orientating SPOT data with as few as 2 GCPs [Dowman et al., 1991]. However, the impossibility of orientating SPOT data with fewer than 5 GCPs, making no use of the header data, was registered during the same tests [Dowman et al., 1991].

The LAI program was developed to accept elements extracted from the header data such as the position, velocity and attitude of the satellite. The initial values of the orientation parameters are estimated from that data. Then, they are corrected according to the observation equations given for each GCP used in the orientation.

The LAI program is able to orientate SPOT data with and without the information given by the header data. In section §4.4.4, real SPOT data was orientated using the LAI program and the SPOT attitude data, extracted from the header. In section §4.4.3, the orientation was made using only ground control.

The orientation algorithm described in this thesis [chapter 3] is able to orientate ACTI with no header data information and a minimum of 5 GCPs. For a smaller number of
ground control, the orientation is performed using only some orientation parameters. The orientation of ALTI is possible without using the header data with a minimum of 3 GCPs identified on both images of the stereopair [§3.6]. An orientation is also possible with 2 GCPs and no additional information, using only a few orientation parameters. However, there may be problems of convergence in this case.

Tests were performed on the orientation of both types of LAI with very few ground control points. The accuracies of the models were very poor in all the cases, with residuals larger than 110m in 3D. Convergence was not achieved for some of the models, and the method described by Westin [1990] to solve these problems and mentioned in §3.2.8, formula [3.32], was tested. However, it did not solve the problem of convergence.

The solution for the orientation of a model with only a few GCPs is the use of header data information. The positioning of the model can be easily corrected a posteriori using the information extracted from the control. The attitude data, extracted from the header, is extremely important for these cases. The orientation parameters related to the attitude may be calculated from this information and only the other parameters are considered variable during the orientation process.

The orientation of models with very few control points and attitude data presumes the study of two cases. The first assumes only the measurement of relative attitude data by the on-board instrumentation. The knowledge of the absolute value of the attitude may be considered as a second hypothesis. In this section, this study is performed for ALTI, with simulated OMI data.

6.7.2. Orientation of OMI models with very few GCPs and different types of attitude data

The tests were performed with the OMI data simulated for a 110km long strip, and using the control configurations shown in figure 6.19. The residuals of the orientation are presented in table 6.13 and are plotted in figures 6.20 and 6.21. The relative attitude data used was simulated to be accurate to 1.0e-6°, and so was the accuracy of the absolute attitude data used.
Chapter 6. Influence of data characteristics on model orientation

Fig 6.19 - Control configurations used for the orientation of OMI stereomodels with very few control points.

<table>
<thead>
<tr>
<th>number</th>
<th>no attitude data</th>
<th>relative attitude data</th>
<th>absolute attitude data</th>
</tr>
</thead>
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<td>GCPs</td>
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<td>3D</td>
</tr>
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<td>7.8</td>
<td>5.0</td>
<td>9.3</td>
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<tr>
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<td>7.9</td>
<td>5.2</td>
<td>9.5</td>
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<td>9.2</td>
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<tr>
<td>2</td>
<td>9.4</td>
<td>7.2</td>
<td>11.8</td>
</tr>
</tbody>
</table>

Table 6.13 - Residuals obtained for OMI stereomodels with very few GCPs and varying attitude data.

The analysis of figures 6.20 and 6.21 shows that better models are achieved if attitude data is used for the orientation of the stereopair. The attitude data improves the accuracy in height but has no effect in plan [Figs 6.20a and 6.20b]. However, the on-board measurement systems only read the relative variation of the attitude of the sensor with time. Using this information, an OMI stereopair may be orientated with only 2 GCPs, with a final accuracy of 9.4m in height and 7.2m in plan.
Chapter 6. Influence of data characteristics on model orientation

Fig 6.20 - Residuals obtained for OMI stereomodels with very few GCPs and varying attitude data (a) in height, and (b) in plan.

Fig 6.21 - Residuals obtained in 3D for OMI stereomodels with very few GCPs and varying attitude data.
6.8. Effect of the accuracy of the attitude data

6.8.1. Introduction

The accuracy of the polynomial used to describe the attitude of the sensor with time depends on the accuracy of the attitude data provided by the on-board measuring system. Used in the orientation process, it will influence the accuracy of the stereomodels. Tests were performed orientating OMI simulated data with very few control points, the same configurations of figure 6.19, and attitude data with different accuracies. Errors were added to the error-free relative attitude data with standard deviation specified for each test.

6.8.2. Tests on the effect of accuracy of attitude data

The different sets of the attitude data used in the tests were accurate to $1.0\text{e}^{-6}$, $1.0\text{e}^{-5}$, $1.0\text{e}^{-4}$, and $1.0\text{e}^{-3}$. The residuals found after the model orientation are presented in table 6.14 and plotted in figures 6.22 and 6.23.

<table>
<thead>
<tr>
<th>no</th>
<th>err = $1.0\text{e}^{-6}$</th>
<th>err = $1.0\text{e}^{-5}$</th>
<th>err = $1.0\text{e}^{-4}$</th>
<th>err = $1.0\text{e}^{-3}$</th>
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<td>2D</td>
<td>3D</td>
<td>H</td>
</tr>
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<td>9.5</td>
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Table 6.14 - Residuals obtained for OMI stereomodels orientated using attitude data with different accuracies.
Chapter 6. Influence of data characteristics on model orientation

Fig 6.22 - Residuals obtained for OMI stereomodels orientated using attitude data with different accuracies (a) in height, and (b) in plan.

Fig 6.23 - Residuals obtained in 3D for OMI stereomodels orientated using attitude data with different accuracies.
Chapter 6. Influence of data characteristics on model orientation

Errors in the attitude data affect strongly the model accuracy in height more than in plan. Although errors of $1.0^{\circ}e^{-4}$ in the attitude data already affect the orientation of the model, this is only severely deteriorated when the error is greater than that value. When 2 control points are used for the orientation, the accuracy in height decreases from 9.4m to 21.2m, for attitude data with errors of $1.0^{\circ}e^{-6}$ and $1.0^{\circ}e^{-3}$, respectively. For the same data, the plan accuracy of the model deteriorates from 7.2m to 10.2m, respectively.

6.9. Effect of control configuration

6.9.1. Introduction and control configurations adopted

A good distribution of the ground control over the model is a requirement to obtain a good orientation. This is easier to ensure for many control points. The accuracy of the model suffers larger variations for different control distribution for a small number of control points.

In this section, only 4 and 3 GCPs were used for the orientation of OMI models, with the distribution shown in figure 6.24. The control was chosen such that the error in the image coordinates was smaller than 1 pixel. Such procedure ensured that the error in the image coordinates, would not affect the results, i.e., to make sure that the variations found would be due to the control configuration and not to errors in the image coordinates.

6.9.2. Orientation of OMI data with different control configurations

The accuracies of the OMI models orientated with the control configurations of figure 6.24 are presented in table 6.15. These residuals are represented in figure 6.25 for height, 2D and 3D. The three configurations CC1, CC2 and CC3 are analysed together, and separately from the other configurations, as they correspond to different orientations of 4 GCPs, while the others use 3 GCPs.
Chapter 6. Influence of data characteristics on model orientation

Fig 6.24 - Different control configurations used for the orientation of OMI stereomodels.

<table>
<thead>
<tr>
<th>control config.</th>
<th>number GCPs</th>
<th>rms (m)</th>
<th>H</th>
<th>2D</th>
<th>3D</th>
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</tr>
<tr>
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<td>7.8</td>
<td>5.6</td>
<td>9.6</td>
<td></td>
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<td>CC3</td>
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<td>9.6</td>
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</tr>
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<td>6.0</td>
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<td></td>
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<tr>
<td>CC5</td>
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<td>9.3</td>
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</tr>
<tr>
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<td>11.0</td>
<td></td>
</tr>
</tbody>
</table>

Table 6.15 - Residuals obtained for OMI stereomodels orientated using very few control points and different control configurations.
Configuration CC1 gives the worse model obtained using 4 GCPs. This may be due to the absence of control in the middle region of the model. Although the accuracy in height is of the same order of the accuracy observed for CC2 and CC3, the accuracy in plan is worse. The 4 GCPs, positioned in the corners, ensure a good modelling of the terrain in height [CC1]. However, this configuration is not the most appropriate. It lacks information along the across and the along track direction. No information is given about any possible deformation that may have occurred along the time of acquisition, nor along the CCD array. The CC3 control configuration covers all the area more reasonably. It ensures that there is information well distributed along the flight direction and this may contribute for the better accuracy observed in plan. The smaller residuals obtained in height for the CC2 configuration may be due to the better information given by the control in the across track direction, although this is not better than the values achieved for CC1.

Fig 6.25 - Residuals obtained in H, 2D and 3D (UTM) for OMI stereomodels orientated using very few control points and different control configurations.
Of the control configurations tested using 3 GCPs, the worst model was obtained with CC4. This configuration fails to cover the imaged area well along the direction of flight. Although the 3 control points of control configuration CC3 are well distributed in the across track direction, they are concentrated on the top and bottom regions of the model. Similarly to CC4, the CC5 configuration fails to give information along the flight direction. This is ensured in CC6, CC7 and CC8. However, the CC7 configuration also fails to give information in the across track direction. This results in a worsening of the model in plan. In CC6 and CC8, the control is well distributed in the along and the across track directions. The slightly worse results observed with CC8 may be due to the linear geometry of the distribution of the control linearly across the model.

In summary, better models are obtained using control configurations well distributed both in the along and across track directions. Configurations with no defined geometric pattern also seem to give better models, e.g., compare results obtained with CC6 and CC8.

A very interesting point to note is the apparent correlation between variations in the accuracies found in plan and the characteristics of the control configurations. A good distribution of the control in the along track direction seems to improve the accuracy in 2D, e.g., compare CC2 to CC3; and CC5 to CC6.

6.10. Effect of ground altitude of the control

6.10.1. Introduction and test data

The aim of this section is to study how the height of the control used in the orientation process affects the orientation of the model. The simulated terrain has an average altitude of approximately 500m, with altitudes varying from sea level to above 1000m, as well as the check points used to test the accuracy of the model orientation. To make sure that the same control configuration was maintained for all tests [Fig 6.1], the
same control points were simulated at different altitudes and were used afterwards for the various model orientations.

6.10.2. Tests with OMI stereomodels

The accuracies of the OMI models orientated using ground control at different altitudes are presented in table 6.16 and plotted in figures 6.26 and 6.27. The tests were performed for a control at approximately 100, 500 and 1000m above the sea level. A forth test was performed with the control at random altitudes between sea level and 1500m. The same check points were used to control the accuracy of the models, with always also varying from sea level to approximately 1500m.

As it may be observed in figures 6.26a and 6.26b, the accuracies of the various models are all very similar in plan. However, when the altitudes of the control are very low, 100m for these tests, the height accuracy of the model deteriorates. This overall effect is then observed in 3D [Fig 6.27].

<table>
<thead>
<tr>
<th>no</th>
<th>Altitude=100m</th>
<th>Altitude=500m</th>
<th>Altitude=1000m</th>
<th>Variable Altitudes</th>
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<tr>
<td></td>
<td>H 2D 3D</td>
<td>H 2D 3D</td>
<td>H 2D 3D</td>
<td>H 2D 3D</td>
</tr>
<tr>
<td>16</td>
<td>8.2 4.6 9.4</td>
<td>7.1 4.5 8.4</td>
<td>7.3 4.6 8.6</td>
<td>7.2 4.5 8.4</td>
</tr>
<tr>
<td>13</td>
<td>8.4 5.0 9.8</td>
<td>7.5 4.6 8.8</td>
<td>7.5 4.9 9.0</td>
<td>7.4 4.5 8.7</td>
</tr>
<tr>
<td>11</td>
<td>8.4 4.8 9.7</td>
<td>7.4 4.8 8.8</td>
<td>7.4 5.0 8.9</td>
<td>7.6 4.8 9.0</td>
</tr>
<tr>
<td>8</td>
<td>8.9 5.0 10.2</td>
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</tr>
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<tr>
<td>4</td>
<td>9.3 5.7 10.9</td>
<td>8.2 5.5 9.9</td>
<td>8.4 5.7 10.2</td>
<td>8.0 5.4 9.6</td>
</tr>
</tbody>
</table>

Table 6.16 - Residuals obtained for OMI stereomodels orientated using ground control at different altitudes.

For a best modelling, the use of all the control at very low altitude should be avoided whenever the average altitude of the terrain is high and the terrain is not flat.
Chapter 6. Influence of data characteristics on model orientation

Fig 6.26 - Residuals obtained for OMI stereomodels orientated with ground control at different altitudes (a) in height, and (b) in plan.

Fig 6.27 - Residuals obtained in 3D for OMI stereomodels orientated with ground control at different altitudes.
Chapter 6. Influence of data characteristics on model orientation

6.11. Orientation of discontinuous LAI

6.11.1. Introduction, test data and control configurations

The LAI program was developed to accept discontinuous ALTI and ACTI data. Discontinuous data taken during the same orbit may be orientated assuming that they are different images of the same strip, with the same viewing angles. This information is easily introduced to the computation through the auxiliary data file.

Tests were performed with OMI and SPOT simulated data as in section §6.2. The discontinuity was created by cutting the data theoretically acquired during the same orbit, into two sets. This way, it was possible to keep the same control configurations [Fig 6.1] for the orientations.

6.11.2. Orientation of discontinuous OMI data

The accuracy of the OMI simulated models are presented in table 6.17 and plotted in figures 6.28 and 6.29. As it can be observed from the analysis of those figures, the accuracy of the continuous or discontinuous OMI data is very similar.

<table>
<thead>
<tr>
<th>number of GCPs</th>
<th>Continuous Data</th>
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</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>H</td>
<td>2D</td>
</tr>
<tr>
<td>16</td>
<td>7.2</td>
<td>4.5</td>
</tr>
<tr>
<td>13</td>
<td>7.4</td>
<td>4.5</td>
</tr>
<tr>
<td>11</td>
<td>7.6</td>
<td>4.8</td>
</tr>
<tr>
<td>8</td>
<td>7.8</td>
<td>5.0</td>
</tr>
<tr>
<td>6</td>
<td>7.9</td>
<td>5.2</td>
</tr>
<tr>
<td>4</td>
<td>8.0</td>
<td>5.4</td>
</tr>
</tbody>
</table>

Table 6.17 - Residuals obtained for OMI stereomodels of continuous and discontinuous data strips.
Chapter 6. Influence of data characteristics on model orientation

Fig 6.28 - Residuals obtained from orientating continuous and discontinuous OMI data (a) in height, and (b) in plan.

Fig 6.29 - Residuals obtained in 3D from orientating continuous and discontinuous OMI data.
6.11.3. Orientation of discontinuous SPOT data

The residuals obtained after orientating continuous and discontinuous SPOT simulated data, are presented in table 6.18. These are plotted in figures 6.30 and 6.31.

<table>
<thead>
<tr>
<th>number of GCPs</th>
<th>Continuous Data</th>
<th>Discontinuous Data</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>H</td>
<td>2D</td>
</tr>
<tr>
<td>16</td>
<td>6.2</td>
<td>11.2</td>
</tr>
<tr>
<td>13</td>
<td>6.9</td>
<td>12.7</td>
</tr>
<tr>
<td>11</td>
<td>6.6</td>
<td>12.5</td>
</tr>
<tr>
<td>8</td>
<td>7.0</td>
<td>13.2</td>
</tr>
<tr>
<td>6</td>
<td>7.2</td>
<td>15.9</td>
</tr>
</tbody>
</table>

Table 6.18 - Residuals obtained for SPOT stereomodels of continuous and discontinuous data strips.

Fig 6.30 - Residuals obtained from orientating continuous and discontinuous SPOT data (a) in height, and (b) in plan.
Chapter 6. Influence of data characteristics on model orientation

Fig 6.31 - Residuals obtained in 3D from orientating continuous and discontinuous SPOT data.

The accuracy of these models varies for both cases studied, with the discontinuous models being less accurate. This effect is observed both in height and in plan.

The accuracy in height is always worse for models with data discontinuity than for the other models. The plan accuracy also tends to be worse for discontinuous models.

6.11.4. Summary of results

The capability of the LAI program to orientate discontinuous LAI data was proved in these tests. The accuracies of the discontinuous models are very similar to those formed with continuous data. However, while no significant differences were found orientating OMI data, a similar effect was not verified with the SPOT data. Discontinuous SPOT models were slightly worse both in height and in plan than continuous models. A maximum difference of 0.9m was found in height, and of 1.0m in plan, between the two models.
6.12. Effect of the knowledge of time acquisition and initial positioning of the sensor

Tests were performed with OMI and SPOT simulated data, to study how the use of the position and velocity of the sensor, and the time of acquisition of the images, given by the header data, affect the model orientation.

The time of acquisition had an accuracy of hundredths of seconds. When orientating SPOT data, this information does not interfere with the computations at all, unless attitude data is also being used or the data set is not continuous. For these cases, convergence was achieved in 4 iterations against the 4 to 6 iterations needed when this initial information was not introduced into the computation. However, tests using exactly the same control revealed that the accuracies of the models orientated with or without using the time of acquisition of the images did not differ by more than 1.1m in 3D.

Similar tests were performed with OMI data. The orientation of ALTI depends on the time displacement parameter, which is directly related to the time of acquisition of the images forming the stereopair. However, the good initial approximation of the time displacement did not influence the accuracy of the models during the tests. The differences encountered were smaller than 0.8m in 3D, and only the number of iterations would sometimes decrease.

Similar effects were registered when the position and velocity of the sensor were initially introduced to the orientation process. When the position, the velocity and the time of acquisition of the images were all initially introduced to the computations, improvements smaller than 0.8m were observed in all the cases. Convergence was achieved in a smaller number of iterations, e.g. 3 to 4 iterations.
6.13. Conclusions

Two types of simulated data were used in this chapter: OMI, used to study the characteristics of ALTI; and SPOT, representing ACTI. The characteristics of the models used were changed from test to test, to study how the model accuracy is affected by these characteristics.

Two tests were performed with OMI data to assess the effect of the quality of the control in the model orientation. Variations in the quality of the image coordinates of the control produce significant variations on the model accuracy. This variation is larger in height than in plan. Errors in the ground coordinates of the control do not affect the model accuracy so strongly. Tests were performed taking the ground coordinates affected by errors as large as 50m and 100m. The results obtained with the very large errors show that an accuracy in 3D is only slightly worse than half of the accuracy of the control ground coordinates.

Some sets of OMI and SPOT data were simulated covering areas with different lengths: 100km, 1500km and 3000km. The OMI models all showed very similar accuracies for all the data lengths considered. However, a significant worsening of the SPOT models accuracy was observed for long strips of data. For example, using 8 GCPs, the 110km SPOT model had residuals of 14.9m in 3D, while an accuracy of 18.6m was observed for the model 3000km long. The use of a larger number of ground control when orientating a very long strip of data (e.g. 3000km) improves the accuracy of the model to the same order of accuracy of shorter strips orientated with less control.

The relationship between the B/H of the model and the accuracy obtained was also tested for the OMI and the SPOT sensors. The larger the B/H, the better is the accuracy of the models. The B/H mainly affects the accuracy in height, which is more significant when the B/H is smaller than 0.6. However, changes in the B/H do not affect SPOT data similarly to OMI data. A similar variation of the B/H results on the very different variations of the accuracy of SPOT and OMI models. While a difference of 7.0m was
found in 3D accuracy for SPOT models, a difference of 9.4m was found for OMI models. The OMI models with B/H=0.5 are significantly worse than the models with B/H=0.6, while SPOT data is affected only for B/H=0.4 or smaller.

Tests performed with stereopairs with similar B/H and different viewing angles present very small differences in the model accuracies. The effect registered on OMI models is almost negligible, suffering variations of 0.4m in 3D for 16 GCPs. SPOT models orientated with more than 10 GCPs and asymmetric viewing geometry tend to get worse in plan than models with symmetric angles. However, for a 16 GCPs configuration, the difference found in the accuracy in 3D is only in the order of 1.3m.

The use of attitude data was also proved to be important for the orientation of OMI data. Information on the relative attitude of the OMI sensor accurate to 1.0°e⁻⁶ may be used to orientate an OMI stereopair with 2 control points, achieving a model accuracy of 9.4m in height and 7.2m in plan. It was also shown that an error on the relative attitude data larger than 1.0°e⁻⁴, if used during the orientation process, severely degrades the model accuracy.

Another aspect studied in this chapter was the effect of the control distribution on the model. It was found that the user should always distribute the control well both in the along and across track directions. It was also observed a correlation between the control distribution and its altitude. It was registered a worsening of the orientation if the control used is all at very low altitude and the terrain is not flat. Better modelling is achieved if the control is chosen at varying altitudes.

The capability of the LAI program to orientate discontinuous data was tested in this chapter. The process consists in using the time displacement parameter to link the images taken during the same orbit. Similar accuracies were found after the orientation of OMI continuous and discontinuous data. However, SPOT discontinuous models are less accurate than continuous. The larger difference was found for an 11 GCPs configuration, with 1.3m in the residuals in 3D.

The LAI program orientates the models with the same order of accuracy, independently from the initial use of the time of acquisition of the images and the positioning of the sensor given by the header data file. Nevertheless, the run time of the program decreases as a consequence of the smaller number of iterations needed for convergence of the process, e.g., 3 to 4 instead of 4 to 6 iterations.
In summary, the identification of the ground control on the imagery must be as accurate as possible for a best model orientation. Very large strips of data should be oriented with more control points than the minimum required for each case. The accuracy of ALTI models is more affected by changes in the B/H than ACTI models are. However, it has the advantage of being orientable with fewer control points than ACTI. The orientation of ALTI models is possible with as many as 3 control points identified per image, and using no on-board measurements. If attitude data is available, it is possible to obtain good ALTI stereomodels using as many as 2 control points.
Chapter 6. Influence of data characteristics on model orientation
Chapter 7.

Accuracy and weighting of the orientation parameters

7.1. Introduction and data used in the tests

A model accuracy depends on the accuracy to which the orientation parameters are estimated. The algorithm developed for the orientation of LAI is an iterative process. It stops when very small corrections are encountered for the orientation parameters. The limit of the corrections setting the convergence of the orientation, also gives the estimated error of the orientation parameters. Hence, the errors on the model accuracy are associated with them.

The variations of the model accuracy resulting from errors in the orientation parameters are studied in this chapter. The effect of the largest error admitted to the orientation parameters is analysed based on these results.

Two types of data were used for testing: simulated SPOT and OMI data. The ground control used for the OEEPE test was used to simulate the two data sets [§4.1.3]. These were initially orientated using the 12 GCPs configuration shown in figure 5.1. Afterwards, small variations were introduced to each orientation parameter and the effect in the model accuracy was evaluated.

The weights to apply to the orientation parameters are also analysed based on these results. Tests are performed to evaluate the influence of the weighting on the final accuracy of the orientation. Two hypothesis are tested. First, it is assumed the orientation
parameters are correlated. Second, they are assumed to be uncorrelated. The weighting matrix takes different forms and the most suitable way of building it is analysed.

7.2. Variation of model accuracy due to residuals in the orientation parameters

7.2.1. Variation of SPOT models accuracy

Table 7.1 shows the errors introduced to a SPOT model in Height (H), East (E) and North (N) [UTM projection] by small variations of the orientation parameters. The variations suffered by the orientation parameters are given for the two SPOT images considered to form the stereopair. The orientation parameters with index 1 correspond to the right image, while those indexed with 2 correspond to the left image. The variations observed are also plotted in figures 7.1 and 7.2.

The most important element of orientation for SPOT imagery is the true anomaly. A variation of about 8m was registered for a variation of $1 \times 10^{-6}$ rad of the true anomaly. Similar variations of $1 \times 10^{-6}$ rad on the other orientation parameters result in smaller effects in the accuracy of the model. Small errors in the true anomaly of either the left or the right orbits of the SPOT images have similar effect on the model. A large variation in the N coordinate will occur as a consequence.

The inclination and the longitude of the ascending node have major influence on the E coordinates. Variations of $1 \times 10^{-6}$ rad of these parameters result in errors of location in E of the order of 3m.

Similar variations of any orientation parameter of the right or the left SPOT images introduce almost similar errors in the model orientation in planimetry. However, the height accuracy of a SPOT model suffers symmetrical variations for similar variations of the orientation parameters of the right and left images.
Chapter 7. Accuracy and weighting of the orientation parameters

Table 7.1 - Variations in rms in E, N and H [UTM projection] of a SPOT stereopair due to small variations of the orientation parameters.

<table>
<thead>
<tr>
<th>orientation parameters</th>
<th>variation (m or rad)</th>
<th>mean error found in metres [UTM]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>East (E)</td>
</tr>
<tr>
<td>Variation in the orientation parameters of the Right image</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(semi-major axis) (a_1)</td>
<td>10m</td>
<td>0.0</td>
</tr>
<tr>
<td>(orbit inclination) (i_1)</td>
<td>(1 \times 10^{-6}) rad</td>
<td>3.2</td>
</tr>
<tr>
<td>(right ascension a.n.) (\Omega_1)</td>
<td>(1 \times 10^{-6}) rad</td>
<td>3.1</td>
</tr>
<tr>
<td>(true anomaly) (F_1)</td>
<td>(1 \times 10^{-6}) rad</td>
<td>-0.6</td>
</tr>
<tr>
<td>(roll) (\omega_1)</td>
<td>(1 \times 10^{-6}) rad</td>
<td>1.2</td>
</tr>
<tr>
<td>(pitch) (\varphi_1)</td>
<td>(1 \times 10^{-6}) rad</td>
<td>0.0</td>
</tr>
<tr>
<td>(yaw) (k_1)</td>
<td>(1 \times 10^{-6}) rad</td>
<td>0.6</td>
</tr>
<tr>
<td>Variation in the orientation parameters of the Left image</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(semi-major axis) (a_2)</td>
<td>10m</td>
<td>0.0</td>
</tr>
<tr>
<td>(orbit inclination) (i_2)</td>
<td>(1 \times 10^{-6}) rad</td>
<td>2.9</td>
</tr>
<tr>
<td>(right ascension a.n.) (\Omega_2)</td>
<td>(1 \times 10^{-6}) rad</td>
<td>3.0</td>
</tr>
<tr>
<td>(true anomaly) (F_2)</td>
<td>(1 \times 10^{-6}) rad</td>
<td>-0.5</td>
</tr>
<tr>
<td>(roll) (\omega_2)</td>
<td>(1 \times 10^{-6}) rad</td>
<td>0.7</td>
</tr>
<tr>
<td>(pitch) (\varphi_2)</td>
<td>(1 \times 10^{-6}) rad</td>
<td>0.0</td>
</tr>
<tr>
<td>(yaw) (k_2)</td>
<td>(1 \times 10^{-6}) rad</td>
<td>0.4</td>
</tr>
</tbody>
</table>

The longitude of the ascending node of the orbit and the roll are the parameters which errors have major influence on the height accuracy of the model. For the orientation of SPOT, an error of \(1 \times 10^{-6}\) rad in the longitude of the ascending node of the orbit introduces a variation of approximately ±4m in height.

The iterative process used for the orientation of LAI is stopped when corrections smaller than \(1 \times 10^{-6}\) rad, 10m, and \(1 \times 10^{-6}\) m are encountered for the angular parameters, the semi-major axis of the orbit and for the time displacement parameter, respectively. An independent variation of each parameter corresponds to the effects presented in table 7.1. However, a combination of possible small residuals in the values of the orientation parameters occur during the orientation process.
Chapter 7. Accuracy and weighting of the orientation parameters

Fig 7.1 - Variations in rms of a SPOT stereopair due to small variations of the orientation parameters (a) in E, and (b) in N [UTM projection].

Fig 7.2 - Variations in rms of a SPOT stereopair due to small variations of the orientation parameters in H [UTM projection].
Tests were performed considering several combinations of orientation parameters affected by small errors. Due to the impossibility of covering all the possible combinations, a few were tested. Only the parameters that have a significant affect on the accuracy of the model were considered. These parameters were the orbit inclination, the longitude of the ascending node, the roll and the true anomaly. The variations assumed were similar to those previously tested and presented in table 7.1, for each parameter. Combinations of two, three, and the four parameters mentioned above were considered.

The maximum variation found in planimetry was obtained combining errors in the inclination, the longitude and the true anomaly of the orbit. Variations of approximately 6m in E and of -11m in N [UTM projection] were observed. The maximum variation found in H, 8m, occurred for tests combining the roll and the true anomaly.

The total effect resulting from small errors in the orientation parameters is accounted for during the adjustment of the observation equations. Hence, the cumulative effect resulting from combining parameters with similar effect on the orientation is prevented. However, the orientation parameters may be over-corrected during the last iteration.

The residuals found orientating SPOT data [Table 4.5] may thus be explained by the errors of the orientation parameters, since they are similar to the results obtained in this section. To confirm this hypothesis, tests were performed changing the correction of the orientation parameters, which sets the end of the iterative process. It was found that if this is set to allow a maximum change of $1 \times 10^{-4}$ rad to the angular parameters and of 100m to the semi-major axis of the orbit, the accuracy of the model is similar to when smaller limits are used to stop the iterative process. It was also verified that the number of iterations does not change.

One last test was performed making one additional iteration after convergence. The corrections found for the orientation parameters after this last iteration were always smaller than $5 \times 10^{-7}$ rad for the angular parameters, and smaller than 22m for the semi-major axis of the orbit. The reason why this limit almost coincides with the limit chosen to stop the iterative process may be explained by the accuracy of the control [§6.3].
Chapter 7. Accuracy and weighting of the orientation parameters

7.2.2. Variation of OMI models accuracy

The variations observed in E, N and H [UTM projection] for an OMI stereopair are presented in table 7.2 and plotted in figures 7.3 and 7.4.

<table>
<thead>
<tr>
<th>orientation parameters</th>
<th>variation (m or rad)</th>
<th>mean error found in metres [UTM]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>East (E)</td>
</tr>
<tr>
<td>(semi-major axis) a</td>
<td>10 m</td>
<td>0.0</td>
</tr>
<tr>
<td>(orbit inclination) i</td>
<td>1x10^-6 rad</td>
<td>5.7</td>
</tr>
<tr>
<td>(right ascension a.n.) Ω</td>
<td>1x10^-6 rad</td>
<td>4.6</td>
</tr>
<tr>
<td>(true anomaly) F</td>
<td>1x10^-6 rad</td>
<td>-0.6</td>
</tr>
<tr>
<td>(roll) Ω</td>
<td>1x10^-6 rad</td>
<td>0.5</td>
</tr>
<tr>
<td>(pitch) φ</td>
<td>1x10^-6 rad</td>
<td>0.0</td>
</tr>
<tr>
<td>(yaw) χ</td>
<td>1x10^-6 rad</td>
<td>2.5</td>
</tr>
<tr>
<td>(time displacement) Δt</td>
<td>1x10^-6 m</td>
<td>-0.1</td>
</tr>
</tbody>
</table>

Table 7.2 - Variations in E, N and H [UTM projection] of an OMI stereopair due to small variations of the orientation parameters.

Small variations in the inclination, in the right ascension of the ascending node of the orbit, and in yaw, introduce large variations in E [UTM projection]. The true anomaly is the element which has major effect in N. Variations of 1x10^-6 rad of the angular orientation parameters introduce maximum errors of 6m in E and in N [Fig 7.3].

Eventual errors in the semi-major axis of the orbit and in the time displacement parameter have major influence in the height accuracy of the model. Surprisingly, errors in pitch do not introduce major variations in altimetry. According to the theoretical study carried out in §3.3.3, it was expected that an error in pitch would affect the height of the model. However, the LAI program orientates the two ALTI images simultaneously. Since the images are from the same orbit, the same orientation parameters are used to orientate both images, the linking being done using the time displacement. Hence, a variation in pitch affects equally the orientation of the two images, and the relative
orientation is maintained. This explains the nil effect in height corresponding to a variation in pitch.

Fig 7.3 - Variations in rms of an OMI stereopair due to small variations of the orientation parameters (a) in E, and (b) in N [UTM projection].

Fig 7.4 - Variations in rms of an OMI stereopair due to small variations of the orientation parameters in H [UTM projection].
As mentioned in section §7.2.1, the results presented in table 7.2 result from considering the independent variations of each orientation parameter. This does not correspond to the situation found during the calculations for model orientation. Therefore, tests were performed considering combinations of the most influencing elements.

The semi-major axis of the orbit, the inclination, the right ascension of the ascending node, the true anomaly, the yaw and the time displacement parameter were considered for the tests. Combinations of two to six elements were studied. The maximum variation found in $E$, 9m, was found combining errors in three orientation parameters: the inclination, the longitude of the ascending node of the orbit and the yaw. Any combination of the mentioned six parameters used did not affect the accuracy of the model in $N$ by more than 6m, while the maximum variation found in $H$ was of 2m.

The limit for the correction to the orientation parameters defining the convergence of the iterative process is set in the LAI program to be $1 \times 10^{-6}$ rad for the angular parameters, 10m for the semi-major axis of the orbit, and $1 \times 10^{-6}$ m for the time displacement parameter. The corresponding effect of such maximum errors in the orientation parameters are the results shown in table 7.2. However, the effect of such errors in the model accuracy is larger than the residuals found orientating OMI data [§5.3.2].

Tests were also performed on OMI data to study the corrections applied to the orientation parameters in an extra iteration, after convergence of the process. The corrections applied to the orientation parameters for the additional iteration were in most cases smaller than $8 \times 10^{-7}$ rad for the angular parameters, and were always smaller than 12m for the semi-major axis of the orbit.

In the case of OMI models, the effect of maximum possible errors in the orientation parameters may be larger than the accuracies found orientating OMI data [§5.3.2]. This effect may be reduced by the combination of the orientation parameters during the least squares adjustment of the observation equations. The only explanation for this effect is the stronger influence of the control accuracy on the modelling process.
7.2.3. Summary of results

The orbital parameters have more influence on the accuracy of the model in plan than in height. Errors in the true anomaly result in variations of the model accuracy in N both in ALTI and ACTI models. The accuracy to which the inclination and the right ascension of the ascending node of the orbit are evaluated has major influence on the accuracy of LAI models in E.

The height accuracy of ACTI models is mainly affected by errors in the right ascension of the ascending node of the orbit. It affects the direction of the rays in the across track direction, and, beside changing the position of the model in the E direction, it will also lower or lift the intersection of corresponding raypairs. This introduces the error, or variation, that was found in height.

The height accuracy of ALTI models is mainly affected by the semi-major axis of the orbit, and by the time displacement parameter. Variations in these parameters will slightly change the base of the stereopair. Accordingly, it will lower or lift the intersection of the raypairs, changing the height of the model.

Tests were performed to study the influence on the model accuracy of combined errors in the orientation parameters. The variations found in the model accuracies due to errors estimating the orientation parameters are very similar to the model accuracies found after orientation. However, additional tests showed that the accuracy of the model does not depend on the maximum error set to the orientation parameters, and used to stop the iterative process. The model accuracy may thus be mainly dependent on the control accuracy and physical and geometric characteristics of the sensor.
Chapter 7. Accuracy and weighting of the orientation parameters

7.3. Weights of the orientation parameters

7.3.1. Introduction

Weighting the parameters used for a model orientation is one way of constraining the values within which these are expected to be. Simultaneously, this may also be a way of giving information about the correlations between the orientation parameters, depending on how the weighting matrix is defined.

If the user assumes the independence of the orientation parameters, the elements of the diagonal of matrix $W_{xx}$ used in equation [3.31] correspond to the inverse of the variance of each orientation parameter. This matrix is defined with \textit{a priori} knowledge, or information on the precision of the initial values of the orientation parameters.

The off-diagonal elements of the matrix correspond to the covariances between the orientation parameters. Statistically, it can be proved that the covariances equal zero for independent parameters. Therefore, the off-diagonal elements of matrix $W_{xx}$ will be zero whenever this independence is assumed.

If the parameters are not assumed uncorrelated, the off-diagonal elements of matrix $W_{xx}$ are the co-factors between each pair of orientation parameters. It has been suggested that the weighting matrix may then be computed \textit{a posteriori} during the first iteration of the orientation process. This proposal is, however, theoretically incorrect since the correlations between the computed parameters arise algebraically; they are not real correlations of observed values arising from physical causes. Nevertheless, this technique was tested and results shown in this chapter demonstrate its ineffectiveness.

7.3.2. Testing user defined weights for the orientation parameters

Assuming that there is no correlation between the orientation parameters, matrix $W_{xx}$ assumes the form given in equation [7.1], where $\sigma_0^2$ is the variance of unit weight.

Matrix $W_{xx}$ is formed using the estimation of the variance of the orientation parameters given by the user. Tests were performed using the same OMI simulated data previously presented in §6.2, and orientated using 8 GCPs as shown in figure 6.1. To
Chapter 7. Accuracy and weighting of the orientation parameters

evaluate the best weights to adopt, tests were performed defining different approximate
standard deviations for the orientation parameters. The accuracy of the weighted models
is presented in table 7.3. More tests were performed but are not presented as the
accuracy of the resulting models was very poor.

\[
W_{xx} = \sigma_0^2 \begin{bmatrix}
1/\sigma_a^2 & 0 & \cdots & 0 \\
0 & 1/\sigma_1^2 & \cdots & 0 \\
\vdots & \vdots & \ddots & \vdots \\
0 & \cdots & 0 & 1/\sigma_r^2
\end{bmatrix}

[7.1]
\]

For comparison purposes, the first model corresponds to a free adjustment of the data.
The standard deviations adopted by the author for each parameter were chosen in
accordance with the study carried out in §7.2. The orientation parameters having
stronger effect on the model orientation should be allowed larger corrections, and larger
standard deviations are assigned to them. The results obtained are plotted in figures 7.5a
and 7.5b.

<table>
<thead>
<tr>
<th>Test</th>
<th>Orientation parameters / Standard deviations</th>
<th>rms (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>a</td>
<td>i</td>
</tr>
<tr>
<td>T0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>T1</td>
<td>10^3</td>
<td>10^{-2}</td>
</tr>
<tr>
<td>T2</td>
<td>10^3</td>
<td>10^{-2}</td>
</tr>
<tr>
<td>T3</td>
<td>10^3</td>
<td>10^{-2}</td>
</tr>
<tr>
<td>T4</td>
<td>10^3</td>
<td>10^{-2}</td>
</tr>
<tr>
<td>T5</td>
<td>10^3</td>
<td>10^{-2}</td>
</tr>
<tr>
<td>T6</td>
<td>10^3</td>
<td>10^{-2}</td>
</tr>
<tr>
<td>T7</td>
<td>10^3</td>
<td>10^{-2}</td>
</tr>
<tr>
<td>T8</td>
<td>10^3</td>
<td>10^{-2}</td>
</tr>
<tr>
<td>T9</td>
<td>10^3</td>
<td>10^{-2}</td>
</tr>
<tr>
<td>T10</td>
<td>10^3</td>
<td>10^{-2}</td>
</tr>
<tr>
<td>T11</td>
<td>10^3</td>
<td>10^{-2}</td>
</tr>
<tr>
<td>T12</td>
<td>10^3</td>
<td>10^{-2}</td>
</tr>
</tbody>
</table>

Table 7.3 - Accuracy of OMI models orientated considering user defined weights for
the orientation parameters.
Chapter 7. Accuracy and weighting of the orientation parameters

Fig 7.5 - Accuracy of an OMI stereopair (a) in H, and (b) in 2D [UTM projection] orientated using user defined weights for the orientation parameters.

All the models orientated using weights are less accurate than the free-adjusted model. There are larger variations in planimetry than in height. However, the tests which tend to give poorer models in plan are also the models with poorer orientation in height. Of the weighted models, those corresponding to tests T1, T3, T4, and T5 gave the worst results.

Test T3 corresponds to the study performed giving a larger standard deviation to the pitch. This procedure makes the corrections to the pitch to be larger during the iterative process, assuming that its initial value is very inaccurate. This may produce oscillations on the correction of pitch due to a correlation with Δt. The effect of errors in pitch on the model accuracy in N (§7.2.2) occurs as a consequence, and is cumulative in the effect affecting orientations T1, T3, T4 and T5.

The four tests T1, T3, T4 and T5 correspond to giving smaller standard deviations to the roll, and of the same order to the yaw. This gives a larger weight to the roll, while yaw is the attitude parameter with more influence on the planimetric accuracy of the model (§7.2.2).
Chapter 7. Accuracy and weighting of the orientation parameters

The estimation of the orbital parameters does not seem to be affected by their relative weighting. Although both the inclination and the longitude of the ascending node of the orbit were found to have major influence on the planimetric accuracy of the model, their relative weighting does not influence the results significantly. This was tested in T6, T7, T8, T9 and T10, with the more accurate models being achieved by T10.

7.3.3. Testing using standard deviations of relative attitude data

When the attitude data given in the header is used for the model orientation, a sixth order polynomial is calculated which gives the attitude for each point in the orbit. The standard deviations of the fitting of these polynomials to the data may be calculated and used to weight the attitude parameters. The OMI data used in the previous test was orientated using the relative attitude data, and weights, giving the results presented in table 7.4, and plotted in figures 7.6a and 7.6b. The values of $\sigma_o=1.6\times10^{-7}$ rad, $\sigma_p=1.9\times10^{-6}$ rad, and of $\sigma_k=4.0\times10^{-7}$ rad, correspond to the standard deviations of the estimated attitude polynomials relative to the header data of roll, pitch and yaw, respectively.

The weights of the orbital parameters were kept constant. The standard deviation of the roll was ensured to be always larger or of the same order as the standard deviation defined to the yaw. This procedure was carried out in order to avoid the large residuals obtained for such cases in tests T1, T3, T4 and T5.

<table>
<thead>
<tr>
<th>Test</th>
<th>Orientation parameters / Standard deviations</th>
<th>rms (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$a$ $i$ $\Omega$ $F$ $\omega$ $\varphi$ $\kappa$ $\omega'$ $\varphi'$ $\kappa'$ $\Delta t$</td>
<td>$H$ $2D$</td>
</tr>
<tr>
<td>T13</td>
<td>- - - - - - - - - -</td>
<td>7.0 5.2</td>
</tr>
<tr>
<td>T14</td>
<td>$10^4$ $10^{-1}$ $10^{-1}$ $10^{-1}$ $10\sigma_o$ $10\sigma_p$ $10\sigma_k$ $\sigma_o$ $\sigma_p$ $\sigma_k$ $10^{-5}$</td>
<td>7.1 5.0</td>
</tr>
<tr>
<td>T15</td>
<td>$10^4$ $10^{-1}$ $10^{-1}$ $10^{-1}$ $3\sigma_o$ $3\sigma_p$ $3\sigma_k$ $\sigma_o$ $\sigma_p$ $\sigma_k$ $10^{-5}$</td>
<td>9.6 21.8</td>
</tr>
<tr>
<td>T16</td>
<td>$10^4$ $10^{-1}$ $10^{-1}$ $10^{-1}$ $\sigma_o$ $\sigma_p$ $\sigma_k$ $\sigma_o$ $\sigma_p$ $\sigma_k$ $10^{-5}$</td>
<td>14.3 22.3</td>
</tr>
<tr>
<td>T17</td>
<td>$10^4$ $10^{-1}$ $10^{-1}$ $10^{-1}$ $10\sigma_o$ $10\sigma_p$ $10\sigma_k$ $10\sigma_o$ $10\sigma_p$ $10\sigma_k$ $10^{-5}$</td>
<td>14.8 23.3</td>
</tr>
<tr>
<td>T18</td>
<td>$10^4$ $10^{-1}$ $10^{-1}$ $10^{-1}$ $10\sigma_o$ $10\sigma_p$ $10\sigma_k$ $0.1\sigma_o$ $0.1\sigma_p$ $0.1\sigma_k$ $10^{-5}$</td>
<td>52.7 206.1</td>
</tr>
</tbody>
</table>

Table 7.4 - Accuracy of OMI models orientated considering user defined weights for the orbital parameters and the estimated accuracy of the relative attitude data.
Chapter 7. Accuracy and weighting of the orientation parameters

Fig 7.6 - Accuracy of an OMI stereopair (a) in H, and (b) in 2D [UTM projection] orientated using user defined weights for the orbital parameters and the estimated accuracy of the relative attitude data.

From the results obtained orientating the model using weights of the same order for the attitude parameters and their rates of change with time, T16 and T17, it is observed that the residuals in height worsen drastically. The residuals are improved significantly if the standard deviation assigned to the attitude bias are larger than those assigned to the rates of change (T16 and T15). It is possible to obtain the same order of accuracy for a free adjusted model and a weighted one, as in T13 and T14.

7.3.4. Using the covariance matrix to describe correlations between orientation parameters

The covariance matrix is computed in the LAI program using the matrix of the normal equations for the first iteration. It is extracted in an intermediate step of the Cholesky method for the inversion of matrices, and is then used for weighting the orientation parameters [Mikhail, 1976; American Society of Photogrammetry, 1980].
Chapter 7. Accuracy and weighting of the orientation parameters

The OMI model had residuals of 7.9m in height and of 6.2m in plan, after being orientated using this method including the use of header data information.

Further tests were carried out with two sets of troublesome data. Three OMI simulated models were orientated using 3 control points and control configurations almost similar to CC4, CC5 and CC8 of figure 6.24. These models were more unstable than those studied in §6.9.2., giving the residuals presented in table 7.5.

<table>
<thead>
<tr>
<th>Test</th>
<th>rms (m) using co-variance matrix [assuming correlated parameters]</th>
<th>rms (m) using weighs as in T2 [assuming uncorrelated parameters]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n iter</td>
<td>H</td>
</tr>
<tr>
<td>T19</td>
<td>6</td>
<td>10.5</td>
</tr>
<tr>
<td>T20</td>
<td>5</td>
<td>9.8</td>
</tr>
<tr>
<td>T21</td>
<td>7</td>
<td>10.7</td>
</tr>
</tbody>
</table>

Table 7.5 - Residuals obtained orientating OMI simulated data, considering correlated and uncorrelated orientation parameters.

The first set of residuals was obtained weighting the orientation parameters using the co-variance matrix as previously described. The second set of residuals was obtained by assuming the orientation parameters uncorrelated, and using weights as in T2 [table 7.3]. It was observed a decrease in the number of iterations needed for convergence of the algorithm, as well as models with smaller residuals.

This method was adopted to test the effect of assuming the orientation parameters correlated. However, the results suggest algebraic correlations due to the extraction of $W_{xx}$ after the first iteration of the process.

7.3.5. Summary of results

From all the tests performed using weights for the orientation parameters, none gave better models than the free adjustment orientation. However, the use of weights may be
helpful when there is no convergence or some special data is used whose accuracy is well specified. During this research, such oscillations in the data never occurred, and this feature could not be tested in that type of situation.

User defined weights should be chosen taking into account the effect of each parameter on the orientation of the model. Parameters equally affecting the model orientation should have weights of approximately the same order. When using the attitude data, or initial estimations of the orientation elements with data extracted from the header data, the orientation of the model may be performed with success, using the estimated standard deviations obtained by comparison of the estimates with the header data.

The use of the covariance matrix does not improve significantly the model relative to the other weighting methods tested. In practice, and contrary to the theory [§3.3.3], none of the weighting matrices adopted for the tests seems to improve the results. Moreover, no strong correlations of the parameters were found during the tests, and no big oscillations of the parameters were found during the orientation processes. This result does not exclude the possibility of the existence of circumstances where weighting matrices are a prime requisite. These should be explored in the future with real data, preferably with ALTI, whenever it becomes available.
Chapter 8.

The use of conjugate points

8.1. Theoretical advantages of using conjugate points

Conjugate points have been used for long in the orientation of aerial photography and of SPOT imagery [American Society of Photogrammetry, 1980; Rodriguez et al., 1988]. Conjugate points are identified in more than one image of the model. While conjugate points will very often correspond to ground control points, it is assumed in this section that the ground coordinates of these points are unknown. However, observation equations may be formed using the pair of image coordinates for each point. The pairs of rays coming from each sensor should intersect in space, and coplanarity equations are formed for each raypair.

This information may be used to improve the relative orientation of the model. It does not influence at all the absolute orientation of the model, and it can be used in two different ways.

First, it can be used in conjunction with ground control. The ground control may be reduced and the number of observation equations required for the model orientation may be completed using conjugate points. In this case, the relative orientation of the model is expected to be improved.

Second, conjugate points can be used alone and a relative orientation of the model should be possible. However, the LAI program is rather different from classical methods of orientating aerial photography. While to perform the relative orientation of aerial photographs is well studied and several methods are common use, it has not been explored for LAI from satellite sensors.
Chapter 8. The use of conjugate points

The French centre IGN has been using conjugate points for the orientation of SPOT imagery for some time [Rodriguez et al., 1988]. This procedure allows SPOT orientation with a reduced number of ground control while still getting good models. Information extracted from the SPOT header data is used to obtain a good initial approximation of the orientation parameters, which is corrected using the conjugate points as well as the control points.

8.2. Introduction of conjugate points to the LAI program

8.2.1. Identification of conjugate points by the LAI program

Conjugate points are control points identified in more than one image of the model, whose ground coordinates are assumed unknown in this section. This information is entered into the LAI algorithm through the control data file [Appendix A]. Once identified, a flag will be given so that this data will be only used to form coplanarity observation equations.

8.2.2. The coplanarity equation for conjugate points

If the model has more than two images, each conjugate point may have been identified in more than two images. This multiple set of observations has to be used in pairs. Each ray pair gives one coplanarity equation, and all the combinations two by two of the total number of images must be considered for each conjugate point.

Let us designate by \([X, Y, Z]^{\top}\) the geocentric coordinates of the conjugate point, and by \([x^+, y^+]\) and \([x^-, y^-]\) the image coordinates of that point. The superscripts (+) and (-) are used to distinguish the parameters, or data, from each image of the pair. Equation [3.16] becomes equations [8.1] and [8.2] for each image.

\[
\begin{bmatrix}
X^+ \\
Y^+ \\
Z^+
\end{bmatrix} = \begin{bmatrix}
X_S^+ \\
Y_S^+ \\
Z_S^+
\end{bmatrix} + s^+ \cdot R^+ \cdot \begin{bmatrix}
0 \\
y^+ \\
f^+
\end{bmatrix}
\]  [8.1]
and

\[
\begin{bmatrix}
X \\
Y \\
Z \\
\end{bmatrix} =
\begin{bmatrix}
X_S \\
Y_S \\
Z_S \\
\end{bmatrix} + s^+ \cdot R^+ \cdot
\begin{bmatrix}
y^+ \\
f^+ \\
\end{bmatrix}
\]

where

\( [X_S^+, Y_S^+, Z_S^+]^T \) and \( [X_S^-, Y_S^-, Z_S^-]^T \) are the geocentric coordinates of the sensor(s);

\( R^+ \) and \( R^- \) are the rotation matrices;

\( s^+ \) and \( s^- \) are the scale factors; and

\( f^+ \) and \( f^- \) are the principal distances for the two images (+) and (-).

Since the geocentric coordinates of the conjugate point are unknown, equations [8.1] and [8.2] cannot be used in that format. They may be combined into one equation [8.3], the equation of a plane. This is the plane formed by the raypair coming from each sensor.

\[
\begin{bmatrix}
X_S^+ \\
Y_S^+ \\
Z_S^+ \\
\end{bmatrix} + s^+ \cdot R^+ \cdot
\begin{bmatrix}
y^+ \\
f^+ \\
\end{bmatrix} =
\begin{bmatrix}
X_S^- \\
Y_S^- \\
Z_S^- \\
\end{bmatrix} + s^- \cdot R^- \cdot
\begin{bmatrix}
y^- \\
f^- \\
\end{bmatrix}
\]

Equation [8.3] takes a more complex form, given by equation [8.4], where \( F_i \) represents the residual due to lack of coplanarity.

\[
F_i = \frac{\left[ (Y_S^+ - Y_s^+)(R_{12}^+ \cdot y^+ + R_{13}^+ \cdot f^+)(X_S^+ - X_s^+)(R_{22}^+ \cdot y^+ + R_{23}^+ \cdot f^+) \right] + \left[ (Z_S^+ - Z_s^+)(R_{12}^+ \cdot y^+ + R_{13}^+ \cdot f^+)(X_S^+ - X_s^+)(R_{22}^+ \cdot y^+ + R_{23}^+ \cdot f^+) \right] - \left[ (Y_S^- - Y_s^-)(R_{12}^+ \cdot y^+ + R_{13}^+ \cdot f^+)(X_S^- - X_s^-)(R_{22}^+ \cdot y^+ + R_{23}^+ \cdot f^+) \right] + \left[ (Z_S^- - Z_s^-)(R_{12}^+ \cdot y^+ + R_{13}^+ \cdot f^+)(X_S^- - X_s^-)(R_{22}^+ \cdot y^+ + R_{23}^+ \cdot f^+) \right]} {\sqrt{(R_{12}^+ \cdot y^+ + R_{13}^+ \cdot f^+)^2 + (R_{22}^+ \cdot y^+ + R_{23}^+ \cdot f^+)^2 + (R_{22}^+ \cdot y^+ + R_{23}^+ \cdot f^+)^2}}}
\]
8.2.3. Treatment of the observation equations from conjugate points

Each pair of conjugate measurements may correspond to two images taken from the same orbit or not. If the two images are not from the same orbit, their orientation will be performed separately and the initial error $E_i$ will be assumed to be half for each image. If the two images are from the same orbit, the orientation is performed all at once and such assumption is not needed. However, there are other changes to consider.

When the pair of images is from the same orbit, equation [3.22] used for the formulation of the problem is kept [equation 8.5]. However, the matrices forming this equation have to be adapted to the data.

\[ A \cdot v + B \cdot \Delta = F \]  

[8.5]

Matrix $A_i$ describing the effect of possible errors in the measurements is given by equation [8.6] where $A_i$ is given by equation [8.7], and $n$ is the number of observation equations.

\[ A = \begin{bmatrix} A_1 & 0 & 0 & 0 & 0 \\ 0 & \cdots & 0 & \cdots & 0 \\ 0 & 0 & A_i & 0 & 0 \\ 0 & \cdots & 0 & \cdots & 0 \\ 0 & 0 & 0 & 0 & A_n \end{bmatrix} \]  

[8.6]

\[ A_i = \left[ \frac{\partial F_i}{\partial x} \frac{\partial F_i}{\partial y} \frac{\partial F_i}{\partial x'} \frac{\partial F_i}{\partial y'} \right] \]  

[8.7]

Matrix $B$ is given by equation [8.8] where each $B_i$ has the form of equation [8.9].

\[ B = \begin{bmatrix} B_1 \\ \vdots \\ B_i \\ \vdots \\ B_n \end{bmatrix} \]  

[8.8]

\[ B_i = \left[ \frac{\partial F_i}{\partial x} \frac{\partial F_i}{\partial y} \frac{\partial F_i}{\partial x'} \frac{\partial F_i}{\partial y'} \frac{\partial F_i}{\partial \alpha} \frac{\partial F_i}{\partial \Omega} \frac{\partial F_i}{\partial \Phi} \frac{\partial F_i}{\partial \omega} \frac{\partial F_i}{\partial \kappa} \frac{\partial F_i}{\partial \kappa'} \frac{\partial F_i}{\partial \Delta \ell} \right] \]  

[8.9]
Matrix $Q$ containing the information on the precision of the measurements will take the form of equation [8.10], where $Q_i$ is given by equation [8.11].

\[
Q = \begin{bmatrix}
Q_1 & 0 & 0 & 0 & 0 \\
0 & \ddots & 0 & 0 & 0 \\
0 & 0 & Q_i & 0 & 0 \\
0 & 0 & \ddots & 0 & 0 \\
0 & 0 & 0 & 0 & Q_n
\end{bmatrix}
\]  

[8.10]

\[
Q_i = \sigma^2_i \begin{bmatrix}
1/\sigma^2_x & 0 & 0 & 0 \\
0 & 1/\sigma^2_y & 0 & 0 \\
0 & 0 & 1/\sigma^2_x & 0 \\
0 & 0 & 0 & 1/\sigma^2_y
\end{bmatrix}
\]  

[8.11]

Vector $F$ is given by equation [8.12] where $F_i$ is not null, and is computed using equation [8.4].

\[
F = \begin{bmatrix}
F_1 \\
\vdots \\
F_i \\
\vdots \\
F_n
\end{bmatrix}
\]  

[8.12]

For conjugate points identified in images from different orbits, matrices $A$, $B$ and $Q$ are similar to those given by equations [8.6], [8.8] and [8.10]. However, the components $A_i$, $B_i$ and $Q_i$ are different, as is each $F_i$.

In this case, only one of the images is orientated at a time (space resection). The value of $F_i$ computed just before the first iteration for the orientation of the first image is assigned to $E_i$. Half of this lack of coplanarity is assumed to be the effect of errors in the orientation parameters of the first image. The other half is the effect of errors in the orientation parameters of the second image. Hence, the value of $F_i$ computed for each iteration, for each image, will be calculated using equation [8.13].
Chapter 8. The use of conjugate points

\[ F_i = \frac{\left( (Y_i^+ - Y_i)^*(X_i^+ - X_i)^*(R_{12}^+ + R_{13}^+ \cdot f^+)^* \right) - \left( (Z_i^+ - Z_i)^*(X_i^+ - X_i)^*(R_{22}^+ + R_{23}^+ \cdot f^+)^* \right)}{\sqrt{(R_{12}^+ \cdot y^+ + R_{13}^+ \cdot f^+)^2 + (R_{22}^+ \cdot y^+ + R_{23}^+ \cdot f^+)^2}} \quad E_i \]

[8.13]

The components \( A_i, B_i \) and \( Q_i \) are now referred to only one image at a time and are given by equations [8.14], [8.15] and [8.16], respectively.

\[ A_i = \left[ \begin{array}{c} \frac{\partial F_i}{\partial x^+} \\ \frac{\partial F_i}{\partial y^+} \end{array} \right] \]

[8.14]

\[ B_i = \left[ \begin{array}{cccc} \frac{\partial F_i}{\partial r} & \frac{\partial F_i}{\partial \alpha} & \frac{\partial F_i}{\partial \Omega} & \frac{\partial F_i}{\partial F} \\ \frac{\partial F_i}{\partial \theta} & \frac{\partial F_i}{\partial \phi} & \frac{\partial F_i}{\partial \omega} & \frac{\partial F_i}{\partial k} \\ \frac{\partial F_i}{\partial \psi} & \frac{\partial F_i}{\partial \omega} & \frac{\partial F_i}{\partial \kappa} & \frac{\partial F_i}{\partial \kappa'} \end{array} \right] \]

[8.15]

\[ Q_i = \sigma_i^2 \left[ \begin{array}{cc} 1/\sigma_x^2 & 0 \\ 0 & 1/\sigma_y^2 \end{array} \right] \]

[8.16]

where \( x^+ \) and \( y^+ \) represent the image coordinates of each point for the image being orientated.

After forming matrices \( A, B, F \) and \( Q \) containing the information extracted from the ground control and the conjugate points, the vector giving the correction to apply to the orientation parameters per iteration may still be computed using equation [3.29]. The weighted parameters solution is also still computed using equation [3.31].

8.2.4. Control requirements

A minimum of two control points per image is advisable for a good absolute orientation of the model. However, more control is needed for an orientation considering all the parameters. Twelve observation equations should be used for a complete
orientation of a LAI stereopair. Each ground control point identified in each image gives two observation equations. The other control used must be enough to complete the required observation equations.

An ALTI stereopair is orientated all at once, since the two images forming the model are from the same orbit. For this case, two ground control points identified on the two images give eight observation equations. If only conjugate points are to be added to this set of control, a minimum of four points is required to obtain the four lacking equations.

For the case of ACTI, the orientation of each image of the stereopair can only be complete with eleven to twelve observation equations. Each ground control gives two observation equations per image, and four are obtained with two GCPs. The other eight equations may be obtained using eight conjugate points.

8.3. Orientation of SPOT data with conjugate points

8.3.1. SPOT test data

The real SPOT data given for the OEEPE test was used for this test [§4.1.3] [Dowman et al., 1991]. The model was orientated without any information from the header data, and only making use of the information extracted from the ground control and the conjugate points. The tests were performed using the configurations presented in figure 8.1.

8.3.2. Results of tests with SPOT data

The results from orientating SPOT data with the configurations of figure 8.1 are presented in table 8.1. These residuals are plotted in figures 8.2a and 8.2b.

The residuals for configurations CC3, CC6 and CC9 are not given. The number of observation equations was smaller than 10 for these cases, and a complete model was not possible without making use of the header data. The iterative process did not converge when fewer than 10 orientation parameters were used.
Chapter 8. The use of conjugate points

**Fig 8.1 - Ground control and conjugate points configurations used in the orientation of SPOT data.**

<table>
<thead>
<tr>
<th>Configuration</th>
<th>No GCPs</th>
<th>No Conj.P.</th>
<th>No Obs. Equats</th>
<th>No iter</th>
<th>rms in m [UTM]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>L  R  H  2D  3D</td>
</tr>
<tr>
<td>8 GCPs</td>
<td>8</td>
<td>0</td>
<td>16</td>
<td>4 4</td>
<td>6.8 12.4 14.1</td>
</tr>
<tr>
<td>CC1</td>
<td>8</td>
<td>3</td>
<td>19</td>
<td>4 5</td>
<td>7.0 12.2 14.1</td>
</tr>
<tr>
<td>CC2</td>
<td>6</td>
<td>4</td>
<td>16</td>
<td>4 5</td>
<td>7.1 16.8 18.2</td>
</tr>
<tr>
<td>CC3</td>
<td>4</td>
<td>2</td>
<td>10</td>
<td>- -</td>
<td>-   -   -   -</td>
</tr>
<tr>
<td>CC4</td>
<td>4</td>
<td>4</td>
<td>12</td>
<td>6 7</td>
<td>14.5 26.2 29.9</td>
</tr>
<tr>
<td>CC5</td>
<td>4</td>
<td>7</td>
<td>15</td>
<td>6 6</td>
<td>14.4 24.5 28.4</td>
</tr>
<tr>
<td>CC6</td>
<td>3</td>
<td>3</td>
<td>9</td>
<td>- -</td>
<td>-   -   -   -</td>
</tr>
<tr>
<td>CC7</td>
<td>3</td>
<td>6</td>
<td>12</td>
<td>8 8</td>
<td>32.2 52.7 61.7</td>
</tr>
<tr>
<td>CC8</td>
<td>3</td>
<td>9</td>
<td>15</td>
<td>8 8</td>
<td>29.2 51.8 59.5</td>
</tr>
<tr>
<td>CC9</td>
<td>2</td>
<td>4</td>
<td>8</td>
<td>- -</td>
<td>-   -   -   -</td>
</tr>
<tr>
<td>CC10</td>
<td>2</td>
<td>8</td>
<td>12</td>
<td>10 12</td>
<td>120.0 231.3 260.6</td>
</tr>
</tbody>
</table>

Table 8.1 - Residuals of SPOT models orientated using ground control and conjugate points.
8.3.3 Analysis of tests orientating SPOT data with conjugate points

The number of observation equations generated by the control decides the convergence, or not, of the orientation algorithm. A complete model uses 10 orientation parameters, and not all the elements are considered if there are less than 10 observation equations. In the tests performed with SPOT data, no convergence was achieved for such cases.

Contrarily to expectations, the accuracy of the model does not improve by adding conjugate points to the control. Sometimes, the number of iterations required for
convergence increases, and the run time of the program doubles. This was observed when orientating the SPOT stereopair using configurations CC7, CC8 and CC10.

Although the accuracy of the models orientated using CC7, CC8 and CC10 is very poor, the orientation algorithm converged. Using the same ground control and conjugate points in number to obtain more than 10 observation equations ensures the convergence of the algorithm.

In order to evaluate the relative orientation of the models, the residuals obtained in the image coordinates of the control were checked. These did not improve with the addition of the conjugate points to the control, and thus, neither did the relative orientation of the model.

8.4. Orientation of OMI data with conjugate points

8.4.1. OMI test data

The OMI data used in this test was simulated using the ground control of the OEEPE test data [§4.1.3]. No information from the header data was used for the orientation. The control configurations adopted are similar to those used for the orientation of SPOT models, and presented in figure 8.1.

8.4.2. Results of tests with OMI data

The accuracy of the OMI models orientated using ground control and conjugate points are presented in table 8.2 and in graphical format in figure 8.3. The residuals found orientating the OMI data using the control configurations CC9 and CC10 are larger than the scale of figure 8.3, and the plotting is not complete.

The orientation of the same OMI data was tested using the header data information, a large number of conjugate points and no ground control. These tests were unsuccessful with no convergence being achieved, due to the oscillation of the iterative process.
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<table>
<thead>
<tr>
<th>Configuration</th>
<th>No GCPs</th>
<th>No Conj.P.</th>
<th>No Obs. Equats</th>
<th>No iter</th>
<th>rms in m [UTM]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>H</td>
</tr>
<tr>
<td>8 GCPs</td>
<td>8</td>
<td>0</td>
<td>32</td>
<td>4</td>
<td>7.9</td>
</tr>
<tr>
<td>CC1</td>
<td>8</td>
<td>3</td>
<td>35</td>
<td>4</td>
<td>7.5</td>
</tr>
<tr>
<td>CC2</td>
<td>6</td>
<td>4</td>
<td>28</td>
<td>4</td>
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</tr>
<tr>
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<td>16</td>
<td>7</td>
<td>50.4</td>
</tr>
</tbody>
</table>

Table 8.2 - Residuals of OMI models orientated using ground control and conjugate points.

Fig 8.3 - Residuals of OMI models orientated using ground control and conjugate points (a) in height, and (b) in plan.
8.4.3. Analysis of tests orientating OMI data with conjugate points

Similarly to what was observed orientating SPOT data, the use of conjugate points does not improve the accuracy of the model. The differences found are not significant and depend mostly on the number of ground control used, rather than on the number of conjugate points.

The residuals of the image coordinates were studied after orientation of the model for most of the control configurations used. The differences found between the various control configurations used were smaller than 0.1 pixel from model to model. The relative orientation of the stereopair did not improve by adding conjugate points to the control.

8.5. Conclusions

The coplanarity equations resulting from considering conjugate points were introduced to the LAI program and were tested on SPOT and on OMI stereopairs. Similar results were observed for both types of data.

The algorithm is very time expensive. First, it introduces a few more equations to the calculation, resulting in the inversion of larger matrices [§3.2.7]. Second, the set of observation equations is not as stable as when only ground control is used. The collinearity and the coplanarity equations tend to give coefficients of very different orders to matrices A, B and F. A deeper study on the subject would be necessary to assess the best process of weighting these equations.

In the tests performed orientating SPOT and OMI data, no significant improvement either in the absolute or relative orientation of the model stems from adding conjugate points to the control. It was also found that the convergence of the algorithm depends on the number of observation equations formed. The absolute orientation of the model gets worse when the number of ground control is decreased, independently from the number
of conjugate points being used. However, conjugate points may be used to ensure a model orientation when the ground control is not enough on its own.

Tests were carried out on the orientation of LAI stereopairs using no control data without success. The orientation algorithm never converges and the relative orientation of the model is impossible.

However, it is expected that three-line stereo systems will overcome this problem of convergence with conjugate points. A larger number of equations per point identified in the images, will contribute towards a more stable solution. The orientation of MOMS or MEOSS models should be tried using this method. Ebner et al. [1992] successfully orientated simulated MOMS data using a very large number of conjugate points.
Chapter 8. The use of conjugate points
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Conclusions

9.1. The LAI orientation model

9.1.1. Linear array imagery

Linear array imagery (LAI) taken from satellite platforms is very stable and several years of research with SPOT data have showed its suitability for map production at 1:50,000. Although this type of imagery may be suitable for map revision at scales smaller than 1:50,000, it is impossible to meet all the requirements to map from SPOT data at such scales. However, two approaches may be adopted. The first approach may be launching sensors with better pixel resolution and the second may be producing new map products, meeting requirements different from those for classical mapping.

The SPOT’s stereo capability and very high resolution have been its main advantages. However, SPOT’s viewing geometry is such that the two images forming the stereomodel are taken from different orbits. Therefore, the two across track images are usually taken several weeks apart, resulting in differences of illumination, also due to the viewing geometry.

Some sensors are already launched and others are under study for launching on satellite platforms in the late 1990s. These are the ASTER, OMI and OPS sensors, all equipped with an along track viewing capability. The images forming along track stereo models are acquired from the same orbit and only a few seconds apart, eliminating the problems previously mentioned of different illumination of the scenes.
9.1.2. The LAI orientation model

Two types of orientation models were considered for development: polynomial or orbital algorithms. Polynomial approaches require a large number of control points for a good orientation of the LAI model, and some researchers also reported that they sometimes misbehave. Additional disadvantages have been reported such as difficulties in orientating long arcs of the orbit, due to a lack of fitting to the elliptical shape of a satellite's motion around the Earth. An orbital approach was thus adopted which solves this problem and with the additional advantage of requiring a smaller amount of control.

The LAI orientation model presented by the author is based on Gugan-Dowman's model for the orientation of SPOT imagery. However, it has been further developed to allow for the orientation of all types of LAI acquired from satellite platforms and with different characteristics.

For this purpose, an additional parameter was added to the four orbital parameters and to the six attitude parameters usually adopted for the space resection of each image. The four orbital parameters describe the position of the sensor in space and its variation along the orbit, while the attitude parameters are used to give the orientation of the sensor and its variation with time. If an image is to be orientated using these 10 orientation parameters, a minimum of 5 control points are required, although 6 are advised.

An along track stereo model is formed by two LAI taken from the same orbit. Therefore, the orbital parameters are the same for both images forming the model, the positions in space differing from each other in proportion to the difference of time of acquisition of each image. The eleventh parameter considered by the LAI orientation program depends on the time displacement between the two images under consideration. This allows the orientation of the second image of a stereopair with only one more parameter. In other words, the time displacement parameter allows the orientation of an along track stereopair with a minimum of 6 control points measured in either image. The most common configuration is to use 3 control points identified in both images of a ALTI stereopair. The only requirement is that a minimum of one control point must be identified in each image, and the other four may be chosen in any of the images.
However, the time acquisition parameter is theoretically highly correlated with the pitch, having the same effect on the imagery as ground relief. Therefore, oscillations of the iterative process may occur. These are constrained in the orientation by weighting of the orientation parameters. The weighting matrix may be created \textit{a priori}, with information about the initial data given by the user. If such information is not available or if it is not reliable, the weighting matrix may also be formed \textit{a posteriori}, using the matrix of covariances computed during the orientation process.

The LAI orientation algorithm also uses in the computation information on the quality of the control used. This feature allows higher weight to be given to the observation equations resulting from more precise control. It may be important in cases where (e.g.) one control point may be very poor, but cannot be rejected in order to keep a pre-defined control configuration.

9.1.3. Capabilities of the LAI orientation model

The LAI orientation model is capable of orientating a maximum of five images, or sets of continuous data, per orbit. A maximum of three orbits may be considered at a time. For each image, or data set, information is introduced through the auxiliary data file on the across and along track viewing angles, pixel size, principal distance, approximate altitude of the sensor and inclination of the orbit.

This enables the use of the program for the orientation of several types of LAI data. The LAI program may thus be used for the orientation of LAI models as follows:

- orientation of across track models formed with two or three images, obtained with the same sensor or different sensors;
- orientation of along track models formed with up to five images taken during the same orbit, obtained with the same sensor or different sensors;
- orientation of hybrid models formed by across and along track imagery with up to three orbits and up to five images per orbit;
- orientation of blocks of data with a maximum of three orbits and up to five images per orbit, with the data acquired from each strip not necessarily overlapping;
- orientation of discontinuous LAI data using the time displacement parameter as a pass-processing parameter; and
Chapter 9 Conclusions

- orientation of LAI data with or without the header data information, namely the attitude data, the position and the velocity of the sensor.

9.2. Accuracy of ASTER, OMI and OPS models

9.2.1. Accuracy forecast of the ASTER, OMI and OPS models

One of the main objectives of this research was to forecast the accuracy of the future along track sensors ASTER, OMI and OPS. Due to non-availability of real data, all the tests were performed using simulated data. A simulation algorithm was specially developed for this work, and the simulation data was validated by comparison of SPOT real data with models obtained using simulated data.

The results obtained from the orientation of the simulated SPOT data differed by less than 10% from the residuals of the real SPOT models for the same control. The analysis of the accuracies obtained in height and in planimetry showed that the same type of accuracy was obtained for simulated and real data. Due to non-availability of along track real data for validation, the same precision was assumed for both across and along track simulated data.

However, although similar accuracies were obtained in planimetry for real and simulated models, an inversion of the residuals in East (E) and North (N) [UTM projection] was observed. Several hypotheses were tested to justify this inversion with no conclusive results. There is thus an unsolved anomaly causing doubt on the simulated data used. However, this does not seem to affect the results in planimetry as a whole, and tests were carried out with this data.

ASTER, OMI and OPS data were simulated for the OEEPE test area from known SPOT data. The characteristics of viewing geometry and orbit parameters were introduced to the simulation program to meet the information given by the bibliography for these sensors.
The rms of an ASTER model is expected to be 25.9m in height and 18.6m in planimetry, if 6 GCPs are used for the orientation. An OMI model is expected to have a 7.9m rms in height and 4.5m in planimetry, also for a 6 GCPs configuration. A similar orientation of the OPS data forms a model with a rms in height of 61.3m and of 16.6m in planimetry.

The results obtained for OPS simulated data are in agreement with the results independently obtained by Shimada et al. [1992] with real OPS data. This result confirms the model’s accuracy forecast made with simulated data for OPS, and it can thus be extrapolated for ASTER and OMI.

The best models are obtained with OMI data and this is due to the better pixel resolution of the OMI sensor: 5m. The pixel resolutions of ASTER and OPS are 15m and 18mx24m, respectively. The higher B/H of the OMI stereopairs (B/H=0.7) is another factor contributing to the better orientations. The ASTER and OPS stereopairs have B/H of 0.6 and 0.3, respectively.

9.2.2. Accuracy of ASTER, OMI and OPS versus SPOT models

The ASTER and the OPS models are less accurate than the SPOT models. The smaller pixel resolution of 10m of the SPOT sensor is the main factor contributing to the better accuracies achieved by the SPOT models. The ASTER or OPS models may never replace SPOT data for map production. Their very low accuracy models may only be used for recognition of changes in very large areas, at very small scales. They may be used in third world unmapped areas or large regions served by out-of-date maps. Only OMI data may be an alternative to SPOT data, and only for some cases.

Although OMI’s pixel resolution is half that of SPOT, the accuracy in height of OMI models is of the same order of SPOT models. Hence, for DEM production, SPOT may still be preferable by the international institutions to the OMI data. However, the planimetric accuracy of the OMI models is twice that of SPOT. Added to this the fact that OMI is an along track sensor thus acquiring the two images just a few minutes apart, with very small differences in illumination, and that it can be oriented with almost half of the control of SPOT data, OMI data may be considered as a substitute to SPOT for some purposes, e.g., for stereo matching.
9.2.3. Accuracy of SPOT models with theoretical along track capability

The so-called SPOT-like theoretical sensors were simulated for this thesis as data with all the SPOT characteristics, and with an along track capability. These sensors were simulated in this research for two purposes. First, they were used to identify the factors contributing to the achievement of different accuracies by the ASTER, the OMI and the OPS sensors, and SPOT. Using this data as an intermediate stage between the ALTI and the ACTI, it was easier to identify if the effects on the models’ accuracies were due to the viewing geometry, along or across track, or due to other physical characteristic such as the pixel resolution or B/H.

The second use of these theoretical sensors was to forecast the accuracy achievable by a SPOT sensor with along track capability. The SPOT models considered during the tests had B/H=0.7, similar to the B/H of the SPOT-OMI data set. This theoretical sensor was simulated considering all the SPOT physical and geometrical characteristics, but adding along track viewing angles similar to those of the OMI sensor.

A SPOT along track model will have the same order of precision in planimetry as the existing SPOT models, but its accuracy in height will be almost twice as bad as that of SPOT. The tests performed with simulated SPOT along track data forecast an accuracy of 11.4m in height and of 9.4m in planimetry using 6 GCPs. An accuracy in height of 6.0m and of 12.9m in planimetry was obtained for the SPOT across track model, with a similar B/H and using the same 6 points as ground control. The accuracy in height of a hypothetical SPOT along track model is improved if the ground resolution of the sensor is also improved.

9.3. Influence of data characteristics on model orientation

Tests performed with OMI and with SPOT simulated data allowed the analysis of the changes in the ALTI and ACTI model accuracies due to variations of the images’
physical or geometric characteristics of the sensor, or of the accuracy of the data used by
the orientation algorithm. From the results of these tests, it was concluded that:

- The accuracy of the models gets worse when the quality of control deteriorates. Errors in the image coordinates have a more noticeable effect on the accuracy of the model in altimetry than in planimetry. Errors in the ground coordinates of the control do not seem to affect the model accuracy as long as they are kept small. It is advisable to use ground control accurate to less than the pixel resolution of the sensor. Tests were performed with ground coordinates of the control with errors up to 50m and to 100m. It was found that the accuracies of the models were half of those of the ground coordinates, in cases when this was larger than the pixel resolution of the sensor.

- The accuracy of the OMI models is forecast not to change much for data strips as long as 110km to 3000km. However, the accuracy of SPOT models orientated with a small number of control points is forecast to worsen in both height and planimetry for long data strips. This becomes significant if less than 13 GCPs are used and for strips as long as 1500km.

- The variations of the viewing angles produce models with different B/H. Tests with simulated data showed that the accuracy of the model decreases with the B/H. Models are stable for B/H larger than 0.6 but lose accuracy if the B/H is smaller. The B/H mainly affects the accuracy in height of both ACTI and ALTI models. However, although ACTI models get significantly worse when the B/H of the model is smaller than 0.5, ALTI models get worse for B/H smaller than 0.6.

- The tests performed to check if the symmetry or asymmetry of the viewing angles of the sensor relative to the vertical would affect the model orientation showed very small variations. The effect on OMI models is almost negligible, while asymmetric SPOT models get very slightly worse relative to the symmetric models.

- It was found that the use of attitude data improves the accuracy in height of an OMI stereopair, with no effect on the planimetric accuracy. A recommendation for using absolute attitude data is indicated by the tests. However, this is not usually given by the header data, and relative attitude must be used instead. This still allows the reduction of the number of control needed for the model orientation, simultaneously improving the model accuracy.
Chapter 9 Conclusions

- The attitude data must be accurate to $1.0^\circ \times 10^{-4}$ if used. Otherwise, the residuals of the model may deteriorate at twice the rate of the residuals found for a model orientated with attitude data accurate to the $1.0^\circ \times 10^{-6}$.

- Tests performed orientating models with very few control points showed an apparent correlation between variations in the model accuracies and the control configurations adopted. A good distribution of the control in the across track direction is essential for a good orientation. A good distribution of the control in the along track direction improves the planimetric accuracy of the model.

- Models orientated with control at altitudes not representative of the ground relief are not as accurate as models orientated using control at various altitudes. If the altitude of the ground is variable, worse orientations are obtained using ground control all at very low altitude, e.g., sea level.

- The LAI program is able to orientate discontinuous data. The accuracy of discontinuous OMI models is forecast to be of the same order of that of continuous data. Although the differences found when orientating continuous and discontinuous SPOT data were not significant, slightly worse models were found orientating discontinuous SPOT data.

- The LAI orientation algorithm described in this thesis, and used for the tests, is not affected by any \textit{a priori} knowledge of the time of acquisition of the images forming the model. Nor is the model accuracy affected by the computation of initial approximations to the orientation parameters from the position and velocity of the sensor given in the header data file. However, the convergence of the algorithm is approximately 80% faster than when such initial data, and initial approximation, are not considered.

9.4. Influence of the accuracy of the orientation parameters

Errors in the estimation of the orbital parameters result in larger variations of the model accuracy in planimetry than in altimetry. All types of LAI models are affected in
N [UTM projection] as a consequence of errors in the true anomaly. The other orientation elements have almost negligible effect in the errors in N. The inclination and the longitude of the ascending node of the orbit are the parameters with major influence in the accuracy of the LAI models in E [UTM projection].

The accuracies in altimetry of ACTI and of ALTI models are affected differently by the model orientation. Errors in the evaluation of the right ascension of the ascending node of the orbit are the main factors responsible for the residuals in altimetry of an ACTI stereopair. The height accuracy of ALTI stereopairs are mainly affected by the accuracy of the semi-major axis of the orbit and the time displacement parameter.

Although the pitch has an effect in ALTI similar to the time displacement parameter, which corresponds to the effect of the relief displacement, errors in the estimation of the pitch do not introduce major errors in altimetry. The LAI program uses the same orientation parameters to orientate both images of an ALTI stereopair, plus one additional parameter for each extra image. The time displacement parameter is used to link the images and simultaneously extends the orientation parameters to longer arcs of the orbit. Errors in the estimation of the pitch affect equally the images of the model. The time displacement introduces a difference in lines for the two orbits, and errors in altimetry occur as a consequence.

The influence of combined errors on some of the orientation parameters is variable. Tests showed that the variations found in the accuracy of the models does not depend on the maximum correction set for stopping the iterations during the orientation process. The model accuracy may thus depend mostly on the control accuracy and on the data characteristics.

9.5. Influence of the weights of the orientation parameters

Theoretically, weights are important to constrain the values of the orientation parameters. The tests performed for this thesis did not confirm the theory. All the tests performed assigning weights to the orientation parameters resulted in less accurate
models. However, weights may be important when there is no convergence of the iterative process. Such cases never occurred during this research, and could not be tested.

If header data is used, it is possible to automatically estimate the accuracy of the initial values of the orientation parameters. This may be used to weight these parameters. The bias of attitude parameters should be weighted approximately ten times less than the rates of change with time. This is due to the high precision of the relative attitude data obtained on-board, and low accuracy of the absolute attitude data.

If the weights are defined by the user, they should be made approximately proportional to the effect of the parameters to the model orientation. The weights also depend on the initial estimation of the parameters, and on the user's capacity to recognise the accuracy of the estimation.

However, it is advisable to first try the orientation of the model using only ground control information and auxiliary data, and an error free adjustment of the data.

9.6. The use of conjugate points in the orientation

Each conjugate point identified in a pair of images introduces one observation equation to the system. These equations give information on the lack of intersection of the ray pairs coming from each image. The correction of this lack of coplanarity should ensure a better relative orientation of the stereopair. However, the tests performed to study the influence of using conjugate points did not confirm the theory.

Introducing conjugate points to the control data file produces more equations to the computations, resulting in an increase in the run time of the program. The absolute orientation of the models is not improved; nor is the relative orientation.

The use of conjugate points is advisable whenever the number of control points is not enough for the model orientation. For such cases, the algorithm will converge only if a number of conjugate points is used with the resulting number of observation equations
being larger than the number of orientation parameters. Although convergence may be achieved when the number of GCPs is very small, the absolute orientation of the model is very poor.

The relative orientation of LAI stereopairs was tested without success. The header data information was used with a large number of conjugate points. The iterative process never converged for any of the studied cases.

The problem of convergence of the orientation of LAI using conjugate points is expected to be overcome for three-line stereo systems. The larger number of observation equations obtained will contribute towards a more stable solution. Additionally, the third image will provide more information, and at shorter intervals, on the sensors' kinematics in space.

9.7. Future developments and research

The future of LAI imagery from satellite sensors depends on its suitability for mapping and to what extent it may substitute classical data such as aerial photography. The accuracy of the information extracted from such imagery depends on the characteristics of the sensors and on the data used for the orientation of the model. In this thesis, the author has studied the influence of some of the characteristics of the initial data and forecast the accuracy of the data to be obtained from future sensors: ASTER, OMI and OPS.

All the tests were performed using simulated data. The data validation was carried out for ACTI, and these results extrapolated to ALTI. However, these results need future confirmation with real data, once this is available. The results obtained separately with OPS real data confirm the forecast made by the author concerning this sensor. However, OPS real data should be orientated using the LAI program for final confirmation of the results obtained with simulated data.

The orientation of discontinuous SPOT data was tested. When available, real SPOT data for longer strips should constitute the basis of a different set of studies. The use of
the time displacement parameter to link discontinuous data for long time separations must be tested. When available, real data of different types of LAI should be used to study the weighting to adopt for the orientation parameters for each type of data. A study of the weighting of the orientation parameters versus the length of the orbit arc should also be performed with real data and compared to the results obtained with simulated data.

One of the main conclusions of this study is the influence of the accuracy and number of control points used on the final model accuracy. It is also known that the cost of orientation of a model is highly dependent on the number of control used, and that it also depends on how that control is acquired. The determination of points on the ground using the Global Positioning System (GPS) is becoming very easy, accessible and a fast method. It gives real time information, with accuracies better than a metre. There is also the advantage of providing information on any chosen point, as long as it is accessible on the ground. Successful results using this type of control may mean its use in areas where ground control is non-existent, ensuring the orientation of models otherwise impossible to orientate, or very expensive to set up.

In a parallel area of research, a process to improve the identification and measurement of the image coordinates of the control should be studied.

The use of on-board GPS devices should also be tested. This information can be extremely useful for a better estimation of the satellite's orbit. A better orbital model may be achieved as a consequence of the very accurate data provided by GPS. If obtained to a better accuracy than that achievable using the on-board measurement systems used (e.g.) by SPOT, it may be possible to orientate the model with a reduced number of control. In fact, the use of GPS receivers on board to provide accurate position of the sensor as a function of time is under study for integration on another future LAI sensor, the Orbital Imaging System (OIS) described by Light [1992].

Tests using conjugate points should be continued. Other techniques should be explored, for example applying numerical scaling to the observation equations to fulfil the coplanarity condition. This should also be tested using sets of three line images instead of the usual stereopair.
REFERENCES


References


References


References


References


References


References

the Workshop on Block Orientation of SPOT Data (OEEPE), University College London, October 1989: 4 pgs.


References


Appendix A

Files used by program LAI.

1. Introduction

The various files called by program LAI are presented in this Appendix:
- file "auxiliary.dat"
- file "time.dat"
- file "data.dat"
- file "attitude.lst"
- file "control.dat"
- file "check.lst".

They give to the algorithm the necessary data for the model orientation. These are described one by one, and examples are given for different types of LAI models.

2. File "auxiliary.dat"

Data concerning the orbital parameters and the sensor's physical characteristics are introduced into the computations through this file.

The main block of this file is composed of a header with the following format:
Appendix A - Files used by program LAI

This file should contain auxiliary data to be used by program LAI

<table>
<thead>
<tr>
<th>2345678901234567890123456789012345678901234567890123456789012345678901234567890</th>
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<tbody>
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<td>parameter</td>
</tr>
<tr>
<td>-----------</td>
</tr>
<tr>
<td>orbit 1</td>
</tr>
</tbody>
</table>

followed by estimations of the semi-major axis, the inclination of the orbit, and its eccentricity, given in the format:

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<thead>
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<tr>
<td>eccentricity</td>
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</tbody>
</table>

The information on the looking angles for each image is inserted in the format:

<table>
<thead>
<tr>
<th>focal(1) (mm)</th>
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</thead>
<tbody>
<tr>
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</tr>
<tr>
<td>along-track angle(1)</td>
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</tr>
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<tr>
<td>along-track angle(3)</td>
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</tbody>
</table>

which is repeated for the number of sensors acquiring imagery during the same orbit pass, as follows:

<table>
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<tr>
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<tbody>
<tr>
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<tr>
<td>along-track angle(1)</td>
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</tr>
<tr>
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<tr>
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</tr>
<tr>
<td>along-track angle(2)</td>
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<tr>
<td>along-track angle(3)</td>
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</tr>
</tbody>
</table>

The LAI program accepts up to 5 images per orbit. An example of a complete block of data for one orbit can be given by:
Appendix A - Files used by program LAI

This file should contain auxiliary data to be used by program LAI

\[234567890123456789012345678901234567890123456789012345678901234567890\]

<table>
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<tr>
<td>inclination (degrees)</td>
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<tr>
<td>eccentricity</td>
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<td>along-track angle(1)</td>
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</tr>
<tr>
<td>along-track angle(2)</td>
<td>20.000</td>
<td></td>
</tr>
<tr>
<td>focal(3) (m)</td>
<td>0.000</td>
<td></td>
</tr>
<tr>
<td>side look angle(3)</td>
<td>0.000</td>
<td></td>
</tr>
<tr>
<td>along-track angle(3)</td>
<td>0.000</td>
<td></td>
</tr>
</tbody>
</table>

A final parameter gives the information on the pixel size of the sensors.

| CDD size (microns) | 8.000 |

If more than one orbit segment is to be orientated, the block of information on the orbit parameters estimates has to be doubled, as well as the information on the sensors for the second, or eventually, third orbit. A final file would have the following format for example:

This file should contain auxiliary data to be used by program LAI

\[234567890123456789012345678901234567890123456789012345678901234567890\]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Initial Value</th>
<th>Disregard? (d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>orbit 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>semi-major axis (m)</td>
<td>7200000.000</td>
<td></td>
</tr>
</tbody>
</table>

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2.1. Orientation of one stereopair of ALTI.

The first example given shows the data initially given for the orientation of an OMI stereopair. Since the two images forming the model were taken during the same orbit, data is only given for one orbit. In this file, approximate values of the orbit eccentricity, of the semi-major axis and of the inclination are introduced. The information on the viewing angles, and on the principal distances of the sensors are also introduced to the computations through this file, for up to three images per orbit. The last value to introduce is the pixel size of the sensor, in µm.
### 2.2. Orientation of one stereopair of ACTI.

The second example shows the auxiliary file for the case of orientation of a stereopair of ACTI data. The two images are taken from different orbits, and data is given for the two orbits.

```plaintext
This file should contain auxiliary data to be used by program LAI

<table>
<thead>
<tr>
<th>parameter</th>
<th>initial value</th>
<th>disregard? (d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>orbit 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>semi-major axis (m)</td>
<td>7200000.000</td>
<td></td>
</tr>
<tr>
<td>inclination (degrees)</td>
<td>98.000</td>
<td></td>
</tr>
<tr>
<td>eccentricity</td>
<td>0.001</td>
<td></td>
</tr>
<tr>
<td>focal(1) (m)</td>
<td>1416.000</td>
<td></td>
</tr>
<tr>
<td>side - look angle(1)</td>
<td>-1.000</td>
<td></td>
</tr>
<tr>
<td>along-track angle(1)</td>
<td>-20.000</td>
<td></td>
</tr>
<tr>
<td>focal(2) (m)</td>
<td>1416.000</td>
<td></td>
</tr>
<tr>
<td>side - look angle(2)</td>
<td>1.000</td>
<td></td>
</tr>
<tr>
<td>along-track angle(2)</td>
<td>20.000</td>
<td></td>
</tr>
<tr>
<td>focal(3) (m)</td>
<td>0.000</td>
<td></td>
</tr>
<tr>
<td>side - look angle(3)</td>
<td>0.000</td>
<td></td>
</tr>
<tr>
<td>along-track angle(3)</td>
<td>0.000</td>
<td></td>
</tr>
<tr>
<td>focal(4) (m)</td>
<td>0.000</td>
<td></td>
</tr>
<tr>
<td>side - look angle(4)</td>
<td>0.000</td>
<td></td>
</tr>
<tr>
<td>along-track angle(4)</td>
<td>0.000</td>
<td></td>
</tr>
<tr>
<td>focal(5) (m)</td>
<td>0.000</td>
<td></td>
</tr>
<tr>
<td>side - look angle(5)</td>
<td>0.000</td>
<td></td>
</tr>
<tr>
<td>along-track angle(5)</td>
<td>0.000</td>
<td></td>
</tr>
<tr>
<td>CCD size (microns)</td>
<td>8.000</td>
<td></td>
</tr>
</tbody>
</table>
```
2.3. Orientation of a hybrid model of LAI data.

Next, an example is given for the orientation of a more complex combination of LAI data. For this example, it is assumed a theoretical situation of the orientation of ALTI data (three images taken in the same orbit), combined with an ACTI stereopair.
Appendix A - Files used by program LAI

This file should contain auxiliary data to be used by program LAI

<table>
<thead>
<tr>
<th>parameter</th>
<th>initial value</th>
<th>disregard? (d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>orbit 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>semi-major axis (a)</td>
<td>720000.000</td>
<td></td>
</tr>
<tr>
<td>inclination (degrees)</td>
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<td></td>
</tr>
<tr>
<td>eccentricity</td>
<td>0.001</td>
<td></td>
</tr>
<tr>
<td>focal(1) (mm)</td>
<td>1416.000</td>
<td></td>
</tr>
<tr>
<td>along-track angle(1)</td>
<td>-20.000</td>
<td></td>
</tr>
<tr>
<td>focal(2) (mm)</td>
<td>1416.000</td>
<td></td>
</tr>
<tr>
<td>along-track angle(2)</td>
<td>20.000</td>
<td></td>
</tr>
<tr>
<td>focal(3) (mm)</td>
<td>1416.000</td>
<td></td>
</tr>
<tr>
<td>along-track angle(3)</td>
<td>0.000</td>
<td></td>
</tr>
<tr>
<td>focal(4) (mm)</td>
<td>0.000</td>
<td></td>
</tr>
<tr>
<td>along-track angle(4)</td>
<td>0.000</td>
<td></td>
</tr>
<tr>
<td>focal(5) (mm)</td>
<td>0.000</td>
<td></td>
</tr>
<tr>
<td>along-track angle(5)</td>
<td>0.000</td>
<td></td>
</tr>
<tr>
<td>CCD size (microns)</td>
<td>8.000</td>
<td></td>
</tr>
</tbody>
</table>

| orbit 2   |               |                |
| semi-major axis (a) | 720000.000 |         |
| inclination (degrees) | 98.000   |         |
| eccentricity | 0.001    |         |
| focal(1) (mm) | 1082.000 |         |
| along-track angle(1) | 0.000    |         |
| focal(2) (mm) | 0.000     |         |
| along-track angle(2) | 0.000    |         |
| focal(3) (mm) | 0.000     |         |
| along-track angle(3) | 0.000    |         |
| focal(4) (mm) | 0.000     |         |
| along-track angle(4) | 0.000    |         |
| focal(5) (mm) | 0.000     |         |
| along-track angle(5) | 0.000    |         |
Appendix A - Files used by program LAI

<table>
<thead>
<tr>
<th>CCD size (microns)</th>
<th>13.000</th>
</tr>
</thead>
<tbody>
<tr>
<td>orbit 3</td>
<td></td>
</tr>
<tr>
<td>semi-major axis (m)</td>
<td>7200000.000</td>
</tr>
<tr>
<td>inclination (degrees)</td>
<td>98.000</td>
</tr>
<tr>
<td>eccentricity</td>
<td>0.001</td>
</tr>
<tr>
<td>focal(1) (mm)</td>
<td>1002.000</td>
</tr>
<tr>
<td>side - look angle(1)</td>
<td>-20.000</td>
</tr>
<tr>
<td>along-track angle(1)</td>
<td>0.000</td>
</tr>
<tr>
<td>focal(2) (mm)</td>
<td>0.000</td>
</tr>
<tr>
<td>side - look angle(2)</td>
<td>0.000</td>
</tr>
<tr>
<td>along-track angle(2)</td>
<td>0.000</td>
</tr>
<tr>
<td>focal(3) (mm)</td>
<td>0.000</td>
</tr>
<tr>
<td>side - look angle(3)</td>
<td>0.000</td>
</tr>
<tr>
<td>along-track angle(3)</td>
<td>0.000</td>
</tr>
<tr>
<td>focal(4) (mm)</td>
<td>0.000</td>
</tr>
<tr>
<td>side - look angle(4)</td>
<td>0.000</td>
</tr>
<tr>
<td>along-track angle(4)</td>
<td>0.000</td>
</tr>
<tr>
<td>focal(5) (mm)</td>
<td>0.000</td>
</tr>
<tr>
<td>side - look angle(5)</td>
<td>0.000</td>
</tr>
<tr>
<td>along-track angle(5)</td>
<td>0.000</td>
</tr>
<tr>
<td>CCD size (microns)</td>
<td>13.000</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3. File “time.dat”

This file should give the information on the time corresponding to the first line of each image. The file is such that each line has to identify first the orbit, followed by the image number and the time corresponding to the first line of the image under consideration. This information is extracted from the header data of the imagery, and it can be transformed into line numbers. It was used in this form in the tests performed for this thesis, for ease of computations.

The values of the line number given for image number 1 of each orbit will be used as the origin for all the computations.

The example given below presents a “time.lst” file for the orientation of two ALTI stereopairs.
Appendix A - Files used by program LAI

1  1  47553.
1  2  -52317.
2  1  -670.
2  2  -25804.

4. File “data.dat”

This file introduces into the LAI program the position and velocity of the sensor for the origin of each orbit under consideration. The following example gives the number of the orbit, followed by the geocentric position (m) and velocity (m/s) extracted from the header of the imagery.

1  5282942.300 468978.349 4870283.946 5042.589 -1089.339 -5357.422
2  4067380.517 526432.248 5029137.720 5338.873 -1056.046 -5155.100

5. File “attitude.lst”

The sensor’s attitude data is introduced to the computations through this file. This is extracted from the header. Any information on the absolute attitude of the sensor is added to the relative attitude data and is introduced into the LAI program through the “attitude.lst” file. An example of such file (shortened) is presented below. The line number is given in the first column, followed by the same parameter given in m, which is not necessary in practise. The values of roll, pitch and yaw are introduced in this order into the computations.

One “attitude.lst” file is needed per orbit, if the user wants to use this information for the model orientation.
Appendix A - Files used by program LAI

<p>| | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>5000</td>
<td>0.1100000E+00</td>
<td>0.2571997E-03</td>
<td>0.1250506E-01</td>
<td>-0.3194501E-02</td>
</tr>
<tr>
<td>6000</td>
<td>0.1320000E+00</td>
<td>0.2585190E-03</td>
<td>0.1250676E-01</td>
<td>-0.3195155E-02</td>
</tr>
<tr>
<td>7000</td>
<td>0.1540000E+00</td>
<td>0.2597926E-03</td>
<td>0.1250794E-01</td>
<td>-0.3195855E-02</td>
</tr>
<tr>
<td>8000</td>
<td>0.1760000E+00</td>
<td>0.2610537E-03</td>
<td>0.1250491E-01</td>
<td>-0.3195562E-02</td>
</tr>
<tr>
<td>9000</td>
<td>0.1980000E+00</td>
<td>0.2622774E-03</td>
<td>0.1250825E-01</td>
<td>-0.3195277E-02</td>
</tr>
<tr>
<td>10000</td>
<td>0.2200000E+00</td>
<td>0.2635189E-03</td>
<td>0.1250794E-01</td>
<td>-0.3195034E-02</td>
</tr>
<tr>
<td>11000</td>
<td>0.2420000E+00</td>
<td>0.2646963E-03</td>
<td>0.1250604E-01</td>
<td>-0.3194775E-02</td>
</tr>
<tr>
<td>12000</td>
<td>0.2640000E+00</td>
<td>0.2659154E-03</td>
<td>0.1250604E-01</td>
<td>-0.3194554E-02</td>
</tr>
<tr>
<td>13000</td>
<td>0.2860000E+00</td>
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</tr>
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<td>14000</td>
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</tr>
<tr>
<td>15000</td>
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<td>0.1250856E-01</td>
<td>-0.3193898E-02</td>
</tr>
<tr>
<td>16000</td>
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<td>0.1250856E-01</td>
<td>-0.3193671E-02</td>
</tr>
<tr>
<td>17000</td>
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<td>0.2717357E-03</td>
<td>0.1250880E-01</td>
<td>-0.3193531E-02</td>
</tr>
</tbody>
</table>

6. File “control.dat”

The ground coordinates of the ground control points used for the model orientation, as well as its image coordinates in the various images are introduced into the program through the “control.dat” file. This takes different forms for different cases, as the “auxiliary.dat” file.

6.1. Orientation of one stereopair of ALTI.

Since the two images of an ALTI stereopair are taken during the same orbit, these are defined only for orbit 1. After defining the orbit in the file, it follows the various ground control points identification and their ground coordinates. For each ground control, it is also defined the image coordinates for each image under consideration.

In front of the ground coordinates of each control point, the information about the accuracy of this control should be inserted, in m. Information on the accuracy of the image coordinates of the control should also be given in front of these, for each image, according to the classification defined in section §4.3.
Appendix A - Files used by program LAI

6.2. Orientation of one stereopair of ACTI.

The images forming an ACTI stereopair were taken from different orbits, and the ground and image coordinates of each control point must be defined for two orbits. An example is given below.

<table>
<thead>
<tr>
<th>orbit 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>ground 501</td>
</tr>
<tr>
<td>image 1</td>
</tr>
<tr>
<td>image 2</td>
</tr>
<tr>
<td>ground 518</td>
</tr>
<tr>
<td>image 1</td>
</tr>
<tr>
<td>image 2</td>
</tr>
<tr>
<td>ground 528</td>
</tr>
<tr>
<td>image 1</td>
</tr>
<tr>
<td>image 2</td>
</tr>
<tr>
<td>ground 1078</td>
</tr>
<tr>
<td>image 1</td>
</tr>
<tr>
<td>image 2</td>
</tr>
<tr>
<td>ground 2002</td>
</tr>
<tr>
<td>image 1</td>
</tr>
<tr>
<td>image 2</td>
</tr>
<tr>
<td>ground 3040</td>
</tr>
<tr>
<td>image 1</td>
</tr>
<tr>
<td>image 2</td>
</tr>
<tr>
<td>orbit 2</td>
</tr>
</tbody>
</table>

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Appendix A - Files used by program LAI

| ground | 501 | 4464484.27 | 447859.57 | 4518316.95 | 2 |
| image | 1 | 0.23 | -1611.44 | 2 |
| ground | 518 | 4538165.36 | 478245.04 | 4411904.55 | 3 |
| image | 1 | 6600.61 | 1507.72 | 2 |
| ground | 528 | 4572751.31 | 459789.57 | 440841.57 | 3 |
| image | 1 | 9034.65 | 936.42 | 2 |
| ground | 1078 | 4558188.39 | 434044.31 | 4426318.49 | 4 |
| image | 1 | 7873.75 | -926.39 | 2 |
| ground | 2002 | 4505581.65 | 466711.40 | 4476364.93 | 2 |
| image | 1 | 3274.76 | 1470.53 | 3 |
| ground | 3040 | 4617272.25 | 449404.12 | 4362855.95 | 3 |
| image | 1 | 12863.76 | 1057.93 | 3 |

6.3. Orientation of a hybrid model of LAI.

In the following example, it is assumed a situation similar to that of §A.2.3. It is assumed a combination of three line ALTI data obtained from the same orbit, plus an ACTI stereopair.

| orbit | 1 |
| ground | 501 | 4464484.27 | 447859.57 | 4518316.95 | 2 |
| image | 1 | -0.59 | -5254.16 | 2 |
| image | 2 | 4.23 | -5453.54 | 2 |
| image | 3 | 1.44 | -6134.54 | 2 |
| ground | 518 | 4538165.36 | 478245.04 | 4411904.55 | 3 |
| image | 1 | 17650.32 | 5564.94 | 1 |
| image | 2 | 15467.28 | 5134.54 | 1 |
| image | 3 | 16236.79 | 5322.42 | 2 |
| ground | 528 | 4572751.31 | 459789.57 | 440841.57 | 3 |
| image | 1 | 25571.81 | 3546.32 | 3 |
| image | 2 | 25397.43 | 3133.73 | 2 |
| image | 3 | 25012.29 | 3420.76 | 2 |
| ground | 1078 | 4558188.39 | 434044.31 | 4426318.49 | 4 |
| image | 1 | 22346.98 | -2764.34 | 3 |
| image | 2 | 21563.99 | -2734.47 | 3 |
| image | 3 | 21143.23 | -2782.07 | 2 |
| ground | 2002 | 4505581.65 | 466711.40 | 4476364.93 | 2 |
| image | 1 | 8557.12 | 5445.43 | 2 |
| image | 2 | 8545.40 | 5134.77 | 2 |
| image | 3 | 8832.43 | 5092.15 | 2 |
| ground | 3040 | 4617272.25 | 449404.12 | 4362855.95 | 3 |
| image | 1 | 35484.71 | 4327.18 | 2 |
| image | 2 | 35501.03 | 4134.61 | 2 |
| image | 3 | 34902.86 | 3634.01 | 1 |

| orbit | 2 |
6.4. Introduction of conjugate points to the computations.

Conjugate points, are introduced to the computations through the "control.dat" file. However, there is a specific letter to define these points. The letter h, or H (standing for homologous) or c, or C (standing for conjugate) should be the first letter of the point identification. Ground control coordinates are not introduced to these points. However, all the information is introduced similarly to the ground control points. The following example shows a control.dat file with a few conjugate points.
### Appendix A - Files used by program LAI

| Image 1 | 16450.32 | 5604.94 | 1 |
| Image 2 | 16556.77 | 5282.36 | 2 |
| Ground 1 | 24630.81 | 3736.32 | 3 |
| Image 2 | 24746.29 | 3380.76 | 2 |
| Ground 2 | 21600.98 | -2585.26 | 3 |
| Image 2 | 21601.23 | -2862.09 | 2 |
| Ground 3 | 8492.12 | 5417.51 | 2 |
| Image 2 | 8825.63 | 5142.00 | 2 |
| Ground 4 | 461727.25 | 449404.12 | 4362855.95 | 3 |
| Image 1 | 35161.71 | 1217.09 | 2 |
| Image 2 | 35162.86 | 3795.01 | 1 |

### 7. File “check.lst”

The check points are introduced to the program through the “check.lst” file. This file has exactly the same form as the control.dat file. However, it contains the ground and the image coordinates of the check points. These are used to check the accuracy of the model orientation, and the accuracy of the measurements are not needed.

| Orbit 1 |
| Ground 501 | 446884.27 | 447859.57 | 4518316.95 |
| Image 1 | -0.49 | -5056.16 |
| Image 2 | 0.11 | -5175.61 |
| Ground 504 | 446907.35 | 502202.23 | 4507677.95 |
| Image 1 | 609.15 | 6738.67 |
| Image 2 | 699.81 | 6502.71 |
| Ground 518 | 4538165.36 | 478245.04 | 4441904.55 |
| Image 1 | 16455.32 | 5604.94 |
| Image 2 | 16556.77 | 5282.36 |
| Ground 528 | 4572751.31 | 459789.57 | 4408441.57 |
| Image 1 | 24630.81 | 3736.32 |
| Image 2 | 24746.29 | 3380.76 |
| Orbit 2 |
| Ground 501 | 446884.27 | 447859.57 | 4518316.95 |
| Image 1 | -0.03 | -1560.18 |
### Appendix A - Files used by program LAI

<table>
<thead>
<tr>
<th>Image</th>
<th>X</th>
<th>Y</th>
<th>Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
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<td>-1611.44</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ground</th>
<th>X</th>
<th>Y</th>
<th>Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>504</td>
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<td>502202.23</td>
<td>1507677.95</td>
</tr>
<tr>
<td>1</td>
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<td></td>
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<tr>
<td>2</td>
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<td>1878.13</td>
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<table>
<thead>
<tr>
<th>Ground</th>
<th>X</th>
<th>Y</th>
<th>Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>518</td>
<td>4538165.36</td>
<td>478245.04</td>
<td>1441904.55</td>
</tr>
<tr>
<td>1</td>
<td>5979.19</td>
<td>1662.29</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>6060.61</td>
<td>1507.72</td>
<td></td>
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</table>

<table>
<thead>
<tr>
<th>Ground</th>
<th>X</th>
<th>Y</th>
<th>Z</th>
</tr>
</thead>
<tbody>
<tr>
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<td>4572751.31</td>
<td>459789.57</td>
<td>4408441.57</td>
</tr>
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<td>8959.85</td>
<td>1087.23</td>
<td></td>
</tr>
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Appendix A - Files used by program LAI
Appendix B

Programs developed for LAI data simulation and orientation.

1. Introduction

A few programs were developed for LAI simulation and orientation, according to the algorithms presented in this thesis. The programs used for this research were all written in FORTRAN and were initially run on a Micro VAX II / GPX workstation at University College London, Department of Photogrammetry and Surveying. They were later compiled to work on Apple Macintosh's personal computers, and they have been also tested on a VAX station 4060 at the Astronomical Observatory of the University of Oporto, Portugal. No differences were found between the versions on the two VAX.

Several versions of the programs were written, in accordance to specific needs of the research, and the natural evolution of the algorithms towards the more complete LAI orientation program. The programs are the following:

- program "formstrip.for"
- program "sim.for"
- program "formfiles.for"
- program "LAI.for"

These are next explained one by one, and examples are given of the interface user-computer. In such examples, the user's type set is shown in bold.
Appendix B - Programs developed for LAI data simulation and orientation

2. Program "formstrip.for"

This program simulates ground control along the region sketched in figure 4.2. This is an extension of the OEEPE SPOT data [Dowman et al., 1991] and the northern and southern limits of the strip are defined by the user. The data created is at an average height of 500m above the ellipsoid. Points simulated in areas corresponding to water basins are excluded from the data set. The program outputs a file called "ground.dat" containing the geocentric coordinates of the simulated control and another called "ground.llh" containing the geographic coordinates of the same control. Next, an example of how to run this program is given, where the users options are presented in bold.

```
URX > run formstrip.exe

> Please Introduce an integer... < seed for random routine
23

> Please Introduce the minimum and maximum
> latitude of the strip to form...
> ... minimum (degrees)...
43

> ... and now the maximum (degrees)...
54

> How many points do you want to create?
> the strip is about 1224km long...
> (please enter an integer...)
530

> program stop
```

Example of a "ground.dat" and of a "ground.llh" output files.

```
URX > type ground.dat

1 4464484.27 447859.57 4518316.95
2 4469917.35 502202.23 4507677.95
3 4500264.09 446178.22 4483699.09
4 4538165.36 478245.04 4441904.55
5 4572751.31 459789.57 4408441.57
```
Appendix B - Programs developed for LAI data simulation and orientation

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URX > type ground.1lh

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3. Program "sim.for"

This program simulates the image coordinates of the control given by any ground.dat. The coordinates of these ground coordinates have to be given in geocentric coordinates, such as in file "ground.dat". The image coordinates are output through file "coordinates.lst", containing all the data in meters and in (line,sample). Data can be simulated for a various number of LAI sensors and orbits.

The next example shows the interface between the user and the computer.

URX > run sim.exe

> Please, input any integer...

73 - seed for random routine

> Please enter number of orbits to consider.

2
Appendix B - Programs developed for LAI data simulation and orientation

> Please choose sensor type of orbit 1:
>  1 - ASTER
>  2 - OMI
>  3 - OPS
>  4 - SPOT

2

> Please enter across track angle of orbit 1 (in degrees)
0.0

> Please enter offset of image 1 (in degrees)
-1.0

> Please enter along track angle of image 1 (in degrees)
20.0

> Do you want to consider another image on orbit 1 (1 - Yes, 0 - No)?
1

> Please choose sensor type of orbit 1:
>  1 - ASTER
>  2 - OMI
>  3 - OPS
>  4 - SPOT

2

> Please enter across track angle of orbit 1 (in degrees)
0.0

> Please enter offset of image 1 (in degrees)
1.0

> Please enter along track angle of image 1 (in degrees)
-20.0

> Do you want to consider another image on orbit 1 (1 - Yes, 0 - No)?
0

> Please choose sensor type of orbit 2:
>  1 - ASTER
>  2 - OMI
>  3 - OPS
>  4 - SPOT

4

> Please enter across track angle of orbit 2 (in degrees)
26.0

> Please enter offset of image 1 (in degrees)
Example of a “coordinates.lst” file:

```
URX > type coordinates.lst

1 0.004683067 0.053909894 610.383 6738.737
2 0.064399671 -0.027152009 8048.559 -3394.001
3 0.131599554 0.044839460 16449.944 5604.932
4 0.197046778 0.029898747 24630.847 3737.343
5 0.171907591 -0.020675057 21488.449 -2584.382
6 0.067934363 0.043334872 8491.795 5416.859
309 0.266078994 0.024413114 33259.874 3051.639
310 0.282162017 0.012687545 35270.252 1585.943
311 0.273755663 -0.008356528 34219.458 -1044.566
312 0.285387643 -0.022518519 35673.455 -2814.815
313 0.282814928 -0.026855702 35351.866 -3356.963
1 0.006497018 0.044496820 213.501 2022.583
2 0.064660721 -0.023415174 2939.124 -1064.326
3 0.131535736 0.036590850 5978.897 1663.220
311 0.274184142 -0.008542253 12058.006 994.472
312 0.285387643 -0.017680705 12960.298 -803.668
313 0.282593331 -0.021349807 12845.151 -970.446
1 0.006523437 0.036590850 296.520 1878.372
2 0.065386830 -0.025024992 2972.129 -1137.500
3 0.133335849 0.03181840 5978.897 1663.220
```

This program also simulates the “attitude.lst” file, or files if more than one orbit is simulated. An example of such file is given in Appendix A. This data is simulated using Westin’s variograms, which has been described in section §3.4.3. Other data created by “sim.for” was already presented in Appendix A, in files “time.dat” and “data.dat”.

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4. Program "formfiles.for"

The data simulated by program "sim.for" are error-free. One of the characteristics of program "formfiles.for" is to add pseudo errors to this data, in accordance to the discussion carried out in section §4.3 of this thesis. The program also re-arranges the data from file "coordinates.lst" into a more appropriate format, directly readable by program LAI. The output are files "control.dat" and "check.lst" presented in Appendix A. The program also uses file "ground.dat", to add the geocentric coordinates of the ground coordinates to the control and check points.

Control which simulated image coordinates are larger than the specifications given for dimensions of the linear array are excluded from the data by this program as well.

```
UXR > run formfiles.exe

> Please, input any integer...
  4 <- seed for random routine

> Please, enter standard error to be considered (in pixels)
  (0 if no error is pretended)
  0.7

> enter the number of orbits considered...
  2

> Which type of image was taken in orbit 1?
  1 - ASTER
  2 - OMI
  3 - OPS
  4 - SPOT

  2

> Please, enter the number of images considered in orbit 1
  1

> Which type of image was taken in orbit 2?
  1 - ASTER
  2 - OMI
  3 - OPS
  4 - SPOT
```

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Appendix B - Programs developed for LAI data simulation and orientation

5. Program "LAI.for"

This program orientates Linear Array stereo Imagery (LAI) from satellite sensors. The programs needs the files described in Appendix A to run. It automatically sets the number of orbits, images per orbit and number of control to consider by interpretation of the data. If no initial data from the header is to be used, empty files can be used instead of files "data.dat", "time.dat" and "attitude.lst".

The interface between the user and the program is as in the example given below:

```
UAX > run LAI.exe

> Please, input the name of file with the control information ( default = control.dat )

control.dat

> reading data from control.dat -->

> Please, input the name of auxiliary file ( default = auxiliary.dat )

aux.dat
```
Appendix B - Programs developed for LAI data simulation and orientation

> reading data from aux.dat -->
> Do you want to consider attitude data for orbit 1? (1=yes / 0=no)

1

> input the name of file with the attitude information (default = attitude.lst)

attitude.lst

> reading data from attitude.lst -->
> computing attitude model...
> Please, input the name of file to write output information (default = out.dat)

output.dat

> Do you want to use the header data positions and velocities of the satellite? (1—Yes, 0—No)

0

> Do you want to consider weights on orbit 1 (1—Yes, 0—No)?

0

> calculating iteration 1
> calculating iteration 2
> calculating iteration 3
> calculating iteration 4

>******************************************************************************
> * ACCURACY OF THE MODEL *
>******************************************************************************

> 6 non-monoscopic points and 0 monoscopic measurements

> MEAN ERRORS FOUND (m) (UTM E,N,H) =
> 0.45  -0.03  -0.27
> RMS OF ERRORS FOUND (m) (UTM E,N,H) =
> 2.53  1.58  4.67
> OVERALL 2D RMS FOUND (UTM PROJECTION) (m) =
> 2.99
> OVERALL 3D RMS FOUND (UTM PROJECTION) (m) =
> 5.54

> Do you want to check the accuracy of the model? (1—Yes, 0—No)

1

> Please, input the name of file with the check information (default = check.lst)
**Appendix B - Programs developed for LAI data simulation and orientation**

check.lst

> reading data from check.lst -->
> checking model...
> 
> ******************************************
> " ACCURACY ON CHECK POINTS"
> ******************************************
> 
> 104 non-monocopeic points and 0 monocopeic measurements
> 
> MEAN ERRORS FOUND (m) (UTM E,N,H) =
> 
> .35  -.38  .90
> 
> RMS OF ERRORS FOUND m (UTM E,N,H) =
> 
> 3.26  2.85  7.04
> 
> OVERALL 2D RMS FOUND (UTM PROJECTION) (m) =
> 
> 4.33
> 
> OVERALL 3D RMS FOUND (UTM PROJECTION) (m) =
> 
> 0.26
> 
> program stop

More information is given through the output file. An example of this file is given below.

UX > type output.dat

> Initial parameters for strip 1
> 
> 0.7200000000E+07
> 0.1710422667E+01
> 0.309729938E+01
> 0.2404059411E+01
> 0.0000000000E+00
> 0.0000000000E+00
> 0.0000000000E+00
> 0.0000000000E+00
> -0.1043625339E+01

> Iteration 1
> 
> 0.7196014686E+07  -0.3985313683E+04
> 0.1722864396E+01  0.1244172941E-01
> 0.309071870E+01  -0.8160067351E-02
> 0.238630651E+01  -0.1712876006E-01
> 0.867169849E-03  0.867169849E-03
> 0.1055812712E-01  0.1055812712E-01
> -0.1783081301E-02  -0.1783081301E-02
> 0.7508243041E-03  0.7508243041E-03
> -0.3266560168E-04  -0.3266560168E-04
> -0.7612418018E-03  -0.7612418018E-03

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Appendix B - Programs developed for LAI data simulation and orientation

```
> -0.7873056714E+00  0.2563196673E+00
> 0.0000000000E+00  0.0000000000E+00
> 0.0000000000E+00
>
>.................. iteration 4
>
> 0.7195325262E+07  0.1390890579E-03
> 0.1722792773E+01  0.1217630766E-07
> 0.3089018775E+01  -0.1226618366E-07
> 0.2387316333E-01  -0.2067768290E-08
> 0.5194978660E-03  -0.1633242527E-07
> 0.1254893666E-01  0.3113105594E-09
> -0.3060686695E-02  -0.8886686662E-08
> 0.2465661677E-03  -0.1242885098E-07
> -0.4086397083E-04  0.4118554041E-08
> -0.2002235443E-03  0.1223623502E-07
> -0.7989070557E+00  -0.2335025267E-09
> 0.0000000000E+00  0.0000000000E+00
> 0.0000000000E+00

>******************************************************************************
> * Values of orientation parameters *
> ******************************************************************************

> STRIP 1 WITH 2 IMAGES

> Semi-major axis = 7195325.262 meters
> Orbit inclin. = 98.7087547 degrees
> Right ascension = 176.9877386 degrees
> True anomaly = 136.7831502 degrees
> Roll = 0.297650 degrees
> Pitch = 7189702 degrees
> Yaw = -.1753799 degrees
> Change of Roll = .0011273 degrees/s
> Change of Pitch = -.0023413 degrees/s
> Change of Yaw = -.014719 degrees/s
> TD of image 2 = -.7989071 meters

>******************************************************************************
> * ACCURACY OF THE MODEL *
> ******************************************************************************

> computed geocentric coordinates
> and model paralaxes dx, dy (m)

> 501 1  -.00000505  0.0000280
> 501 2  .00000212  0.0000037
> 501 4  4464487.444  447820.033  4518321.210
> 501 5
>
> 518 1  0.00000385  -.00000117
> 518 2  0.00000544  .000000112
> 518 4  4538268.255  478244.502  4441903.327
> 518 5
>
> 528 1  -.00000064  -.00000686
> 528 2  .00000040  .00000013
> 528 4  4572754.299  459787.639  4408443.443
> 528 5
>
> 1078 1  0.00000338  -.00000169
> 1078 2  -.00000368  -.00000453
> 1078 4  4558184.508  434042.045  4426315.133
> 1078 5
>
> 2002 1  0.00000332  0.00000272
> 2002 2  -.00000661  -.00000313
> 2002 4  4505575.781  486711.051  4476360.383

```

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Appendix B - Programs developed for LAI data simulation and orientation

Residuals of model in line and sample on strip 1 are
mean x = -.00000010  mean y = .00000072
rse x = .00000425  rse y = .00000475

6 non-monoscopic points and 0 monoscopic measurements

MEAN ERRORS FOUND (m) (UTM E,N,H) =
 .46  .02 -.27

RMS OF ERRORS FOUND m (UTM E,N,H) =
 2.56  1.55  4.56

OVERALL 2D RMS FOUND (UTM PROJECTION) (m) =
 2.99

OVERALL 3D RMS FOUND (UTM PROJECTION) (m) =
 5.46

******************************
* ACCURACY ON CHECK POINTS *
******************************

computed geocentric coordinates
and model paralaxes dx,dy (m)

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</table>
Appendix B - Programs developed for LAI data simulation and orientation

> 3042 1 -0.0000969 -0.0000115
> 3042 2 -0.0000155 0.0000162
> 3042 4608553.761 448269.298 4372052.528
> 3048 1 -0.0000084 0.0001157
> 3048 2 0.0000423 0.0000492
> 3048 4616806.930 439002.972 4364378.253
> 3053 1 -0.0000049 0.0001571
> 3053 2 0.0000180 0.0001112
> 3053 4611815.725 427824.075 4370645.005
> 3035 1 -0.0000096 -0.0000076
> 3035 2 -0.0000080 0.0001715
> 3035 4617450.105 417717.718 4365339.820
> 101 1 -0.0000551 0.0000254
> 101 2 0.0000544 0.0001767
> 101 4615990.278 415536.350 4367096.142
>
> Residuals of model in line and sample on strip 1 are
> mean x = .00000049  mean y = .00000070
> rms x = .00000641  rms y = .00000668
>
> 104 non-monoscopic points and 0 monoscopic measurements
>
> MEAN ERRORs FOUND (m) (UTM E,N,H) =
> .35  -.35  1.00
> RMS OF ERRORs FOUND m (UTM E,N,H) =
> 3.25  2.85  6.97
> OVERALL 2D RMS FOUND (UTM PROJECTION) (m) =
> 4.32
> OVERALL 3D RMS FOUND (UTM PROJECTION) (m) =
> 8.20
Appendix C

Definitions.

A **STRIP** consists of a continuous set of ground data, which identifies the ground area imaged by one or more sensors one or more times.

An **ORBIT** is the satellite path in space, corresponding to the time of imaging a certain region on Earth. The term **orbit** is usually used as an abbreviated form for an arc of the orbit.

One **IMAGE** is a set of data, continuous or not, acquired from one single orbit, using a single sensor. A **Linear Array Image (LAI)** is a set of data acquired from a LAI sensor, e.g., SPOT, OMI, etc..

One **SCENE** is a set of data corresponding to a pre-defined area/dimensions. LAI scenes are sets of data truncated every n number of lines, specified for each sensor.