The Generation of Epipolar Synthetic Stereo Mates for SPOT Images using a DEM.

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ABSTRACT

In order to test image matching algorithms on SPOT data it is frequently necessary to use data which has been resampled into epipolar lines. This can only be achieved directly with the use of a DEM. A suite of programs has been written in the C programming language and implemented on SUN workstations to carry out this process. The suite contains a model of the SPOT camera system and a ray tracing procedure so that an image can be projected onto the DEM and reprojected onto a new image plane along epipolar lines. The system can be used to build up synthetic images by transferring brightness from a SPOT image into an idealised camera system, or to identify data which should fall on given epipolar lines, and reconstruct new images by resampling. An estimate of the error budget associated with the model and resampling system is given. The system will be primarily used as a source of epipolar data for testing stereo matching algorithms. The system may also be used to investigate the effects of camera attitude on image epipolarity in a controlled fashion. The construction of epipolar images without the use of a DEM is considered as an extension of this work

1.0 Introduction

The potential of SPOT imagery for mapping has now been established, particularly in papers presented at the SPOT Symposium held in Paris in November 1988. The geometry of the sensor is also well known and a number of solutions have been developed and implemented (Dowman, 1988 - Review paper at Paris). A considerable amount of work has been carried out at University College (UCL) on the development of a SPOT model, assessment of accuracy for mapping and the use of SPOT data for image matching (Dowman et al, 1987; Muller et al, 1987; Day and Muller, 1988). This paper describes work carried out as part of a project supported by the Alvey Directorate in the UK in the area of information technology, the project is concerned with the development of a real time 2.5D vision system which can be applied to SPOT images, photographic images or close range digital images. Certain algorithms for image matching require epipolar data which , in the case of SPOT, must be obtained by resampling the original data with the aid of a digital elevation model (DEM). A production system using these algorithms will clearly need a system to produce epipolar data without the use of a DEM, and this is a matter of current consideration which will also be considered in this paper. The main purpose however is to describe the software which has been developed to produce epipolar images using a DEM but which has widespread application to future work, including the production of orthophotographs and stereomates.

The Alvey MMI-137 project has coded and investigated a number of stereo matching algorithms, including the PMF algorithm (Pollard et al, 1985; Chau, 1987) the Banard and Thompson algorithm (Banard and Thompson, 1980; Collins et al; 1987) and the Gruen algorithm, (Gruen and Baltsavias, 1987; Chau and Otto, 1988). All of these algorithms attempt to match groups of corresponding pixels in the left and right images of a stereo pair. Once such matching pixels have been found, an estimate of the position of the corresponding object point may be found by putting the pixel positions identified into a suitable camera model, in this case the SPOT-1 camera model (Gugan and Dowman, 1987) and finding the intersect point of the emergent rays from each of the two camera positions used to view the image. One of the stereo correspondence algorithms which are being investigated, the PMF will only produce meaningful disparities if the stereo image pair lie along epipolar lines.

The paper first discusses the problem s involved in epipolar resampling and then describes the geometric modelling system including the ray tracing and resampling techniques. Results are presented and some future work is discussed.

2.0 Problems inherent in epipolar resampling of SPOT data

If a pair of images are epipolar, corresponding points of detail which lie on a straight line on one image, also fall on a straight line in the corresponding image. For geometry such as the SPOT-1 camera, this means that disparities or parallax are constrained such that they lie in the direction of the image scan-lines only.

In order to generate a pair of epipolar images, both SPOT-1 sensors must lie in a vertical plane passing through the swathe of terrain to be recorded. For the production of an epipolar image pair, the only parameter which remains unconstrained is that component of the perspective centre position vector which is parallel to the direction of the camera sensor array.

Given that the SPOT-1 camera is orbiting the earth, without attitude control it is clearly unreasonable to expect that the constraints required to attain epipolar images can be attained in practice. A typical SPOT-1 level 1A (raw) stereo image pair is shown in figure 1a. As it may be seen, the satellite attitude is very different in the two images. In fact, due to limitations inherent in the SPOT-1 satellite system, not only are the two images taken from cameras whose attitudes differ, they may also be taken at different times of year. Even given that the differing camera attitude can be corrected for, the differing image acquisition times can mean that matching the image pair may be a considerable heuristic feat for the stereo correspondence algorithms.

Otto (1987), has shown that it is not possible to directly resample raw SPOT-1 level 1A images to an epipolar geometry without apriori knowledge of the underlying terrain. Before proceeding with a discussion of these difficulties it may be instructive to modify the existing definition of what is meant by the term epipolarity. Two images may be defined as being epipolar, given that the linearity of scan lines is preserved when pixels in image 1 are transformed to their corresponding positions in image 2 by ray tracing via the terrain. In an untilted local vertical co-ordinate system, because the SPOT-1 sensor has an along-track look angle of ~0.53 degrees, a linear scan line will not in general be transformed into a linear scan line in the second image. The errors due to the along track sensor look angle amount to 1 pixel for relief differences of ~1000 metres. Given the along track look angle, the set of pixels in the second image which correspond to a scan line of pixels in the first will be a function of relief. The functional form of the image 2 scan line will be related to the detail of the terrain. The magnitude of the deviations from the idealised epipolar scan-line will be related to the height of terrain above the datum of the local vertical system.

3.0 Overview of the SPOT-1 geometric modelling system.

A system has been developed within the department of Photogrammetry and Surveying at University College London, for the epipolar resampling of SPOT-1 level 1A data using a suitable digital elevation model(DEM). An overview of the model is shown in figure 2. The system is subdivided into a number of distinct components.

(a) The input output module.
(b) The camera model initialisation model.
(c) The SPOT-1 geometric camera model.
(d) The idealised cylindrical geometry camera model.
(e) The co-ordinate interconversion module.
(f) The fast ray tracer.

3.1 The input output module.

The function of this module is to read in the data which is required by the rest of the system. In the present version of the geometric camera modelling system, there are two principal forms of data required. Firstly there is the raw SPOT-1 level 1A sub-image which is to be resampled and its corresponding digital elevation model. These datasets are stored using the HIPL picture/header format, described by Landy and Cohen (1982). A steering file is also required which contains the absolute orientation parameters of both the SPOT-1 and idealised camera models, and a list of textual instructions which describe to the system the operation which is to be performed on the input data. In order to reduce the amount of typing required of the user, the HIPL header of the SPOT-1 level 1A input image contains a dependency tree. This dependency tree is used by the input/output module to automatically reference all data objects which will be required by the system to process the image.

3.2 The camera initialisation module.

This module is used to set up a given camera model prior to using it within the modelling system. In future versions of the code, this module will also be responsible for reading in the absolute orientation data required by a given module, thus increasing the generality of the input output module, which will then deal only with those items of data which are independent of the camera model being used. A camera initialisation module will be associated with every camera model which is interfaced to the geometric camera modelling system.

3.3 The SPOT-1 Geometric camera model.

The SPOT-1 geometric camera model permits transforms between object space co-ordinates (x,y,z) and image space co-ordinates (x,y), (x',y'). The SPOT-1 sensor model is derived from that developed at UCL by Gugan and Dowman, for the Kern DSR-1 analytical plotter. This sensor model is described in detail by Gugan (1987). The geometric sensor model takes account of some, but not all of the perturbations in sensor attitude as the image was acquired.

The implementation of the SPOT-1 sensor model for the geometric camera modelling system incorporates a number of refinements. In particular, extensive use has been used within the model algorithm of look up tables which store values which would otherwise need to be frequently recalculated. The prime reason for these improvements is the emphasis which must be given to execution speed of execution within the geometric modelling system: To generate an image of some 1200 by 1200 pixels involves the tracing of about 2,000,000 rays from the SPOT-1 image to the idealised image. Thus, any factor which may increase the execution speed of any module which lies within the time critical ray tracing loop is worthy of investigation. Gugan reports run time savings of up to 30% of total run-time are attainable by the PDP 11/73 computer which controls the DSR-1 when look up tables are introduced into the SPOT-1 camera model.

3.4 The idealised SPOT model.

The idealised SPOT camera model is a much simplified version of the SPOT-1 sensor model. All the scan lines in the model are fixed relative to each other. Hence there can be no geometrical distortion effects due to yaw pitch and roll, as there are in the SPOT-1 camera model. The idealised camera model may be freely oriented in the local vertical co-ordinate system within which it is defined. In addition, there are facilities within the model to tilt the image plain. These facilitates have been included so that camera attitude effects may be studied with the geometrical camera modelling system. Functionally, the idealised camera model has the same interface as the SPOT-1 camera model, and indeed it is hoped all future camera models which may be interfaced to the system.

3.5 The co-ordinate interconversion module.

The purpose of co-ordinate interconversion modules is to transform between the co-ordinate systems in which given camera models are defined. In the case of the SPOT-1 to idealised resampling system a co-ordinate conversion module is required to transform between the geocentric co-ordinate system in which the SPOT-1 camera model is defined, and the local vertical system in which the DEM and the idealised camera model are defined.

3.6 The ray tracing module.

In general, a ray from a given pixel in the SPOT-1 or ideal camera models will not intersect the DEM at one of the sample points for which it is defined. Therefore, a ray tracing module has been developed. This ray tracing module permits the intersection point of rays from a camera model with the DEM to be estimated. To simplify the operation of ray tracing, the DEM and the ray vector are expressed in a local vertical co-ordinate system which is derived from the geocentric co-ordinate system using the co-ordinate transformation modules which have been described above. The DEMs used as test data are initially expressed in the French Lambert co-ordinate system. As a consequence of this the error involved in transforming the Lambert zone 3 co-ordinates to local vertical co-ordinates via the geocentric system have been investigated. Analysis of the variation in DEM side length and of the angle between the sides of the DEM when transformed from the Lambert Zone 3 system, to a local vertical system, which is based upon a tangent-plane to the earth geoid, centred at (0,0,0) local vertical co-ordinates, indicates that errors are negligible, provided that area of the DEM is small compared to the total surface area of the earth. It is is allowable therefore, to simplify the ray-tracing calculation by treating the DEM as a flat plane, the corners of which are defined by the transformed Lambert zone 3 co-ordinates in the local vertical system. The DEM plane may then be considered as being subdivided into a mesh, the node points of which are at the same height as corresponding node height within the original DEM expressed in the Lambert zone 3 co-ordinate system. Furthermore, the spacing between these nodes can be considered to be the same as the spacing between neighbouring points in the original DEM

The purpose of the ray tracing operation is to grab brightness from the input image and to map it into the output image. In order to avoid gaps appearing in the pixelation of the output image, rays are traced from the input space (the idealised SPOT model), to the output space, (the SPOT-1 camera model).

In order to ensure that there are no gaps in the pixelation of the output space, the pixels in the output space are chosen at integer values of i and j. The intersection point of the corresponding ray emerging from the ideal camera model is then found on the DEM. The ground intersection co-ordinates are then passed to the SPOT-1 camera model and the corresponding pixel position in the SPOT-1 image is identified. Because the SPOT-1 and ideal camera models will not be in similar orientations, and of relief effects, the pixel position in the SPOT-1 image will in general be non integer. In order to extract the required brightness, a bi-linear interpolation scheme is used, in which a weighted sum of the four neighbouring integer pixels, for which the grey level is known, is formed

A schematic showing the principles behind the ray tracing operation, which itself uses bi-linear resampling to estimate the intersection point of the ray with the DEM is shown in figure 3.

In addition to the method indicated in the schematic, the intersection point between the ray being traced and the DEM, Pi, may be found to even greater accuracies using a binary search techniques. The solution space is defined as that region of space in which the actual solution point Pi lies. Without any refinement of Pi, the solution space is a linear region bounded by the points P1 and P2, as the incident ray must intersect the DEM somewhere on a line joining these two points. In practice, it has been found that adequately resampled SPOT images may be generated without having to use the binary solution space reduction algorithm described above.

In the early stages of the development of the ray tracing module, a number of alternative strategies were looked at. A version of the ray-tracer using conventional vector intersection of a set of triangulated planes, derived from the DEM was developed. This algorithm proved to be slow. Rendering an image of 512 pixels square took 170 minutes on a Sun 3/180C workstation. The fast ray tracing technique described above took 60 minutes to process the same image on the same hardware. The quality of the resampled images produced by the fast ray tracer were found to be of superior quality to those produced by the other ray tracing methods investigated.

3.6 Design Philosophy of the geometric camera modelling system.

The design of the geometric camera modeller software follows that of a typical software integrated circuit (IC). A software IC is a collection of building blocks with a well defined interface, or binding, to other 'building blocks' within the software IC. In the geometrical camera model there are three levels of building blocks available from which a new system component may be built.

3.61 The primary level of the system.

At the lowest level, there are a number of libraries which provide utilities which are often required by the programmer in building new programs. At the present time, these support libraries include:

a) A standard input output library. This provides a standard way of decoding UNIX-style command line tails.

b) A utilities library, which provides functions and procedures which are used a lot in the geometrical camera modelling system, but which are not standard UNIX or C library function.

c) The vector arithmetic library. This provides all of the vector operators likely to be required in ray tracing/photogrammetric applications software.

d) The HIPS library. This library is essentially the same as that defined by Landy and Cohen (1982) in the HIPL picture/header format standard. A number of additional components have been added to the library. These components allow data dependency trees within the HIPS header, and dynamic allocation of data storage for the binary component of HIPS files.

3.62 The secondary level of the system.

The libraries which comprise the next level of 'building block' in the software IC have already been documented. They are the high level camera model, ray tracing, co-ordinate conversion and input/output procedures which have been described above.

3.63 The tertiary and quaternary levels of the system.

The highest level building blocks in the geometrical camera modelling system are programs, which operate on specific argument data objects. In the UNIX environment, these high level building blocks may be interconnected by UNIX pipes under the control of the UNIX shell, thus allowing complex image processing operations to be executed.

Although it is coded in C rather than Pascal, the geometrical camera modelling system, owes much to an earlier system, developed by O'Neill (1988). It inherits many of the earlier systems features. The well defined structure of the code means that the system is easy to maintain, and, using the libraries provided, to add new components to the system. The system is thus easy to maintain and readily adapted to the precise requirements of a given institution.

4.0 Results.

The end product of the system is a stereo pair or triplet (right left and vertical) which are effectively stereo mates in which the parallaxes are identical to those which would be present on an ideal image. Examples of these images are shown in figure 1b. The precision of the resampling can be tested by measuring image coordinates of conjugate points and comparing y coordinates. Tests on a number of points indicate that y parallax errors amount to no more than 2 pixels and is generally less than 1 pixel.

Accuracy can be measured by comparing the line and sample co-ordinates of points in the left and right images, and then computing the resulting disparity or parallax. If the image is ideally epipolar, then the residual line parallax should be zero. The results of stereo measurements on 10 points chosen at random across the idealised images are shown in table 1 below.

Line.	Sample.	Line disparity.	Sample Disparity.
130.750	175.250	1.750	-20.000
160.500	157.500	1.500	-20.000
269.250	239.250	1.250	-38.250
404.000	234.000	1.750	-20.750
445.000	258.000	1.750	-18.500
477.500	583.000	2.000	-29.000
604.000	559.500	1.750	-28.750
70.500	115.750	2.000	-21.750
38.500	118.250	2.000	-23.000
398.000	205.750	1.000	-21.500

Table 1. Showing the results of stereo measurements made on the resampled epipolar images.

5.0 Discussion and future developments.

A process has been described whereby new images of an ideal geometry can be produced from SPOT data of known orientation. Camera models can be defined and ray tracing methods used to construct the new images to any desired specification. The software has been written in modular form to allow programs to be built up for different applications. The application described and tested is for the production of epipolar images produced using a DEM for testing correlation algorithms; these images have been produced from the originals by resampling and have been tested for geometric accuracy.

The next requirement in the Alvey 2.5D vision project is to produce epipolar images without the use of a DEM. This is not possible directly because a terrain height is needed to project from an ideal model into the real model. Otto (1987) has shown that a envelope of can be defined in which the epipolar data lies and that the accuracy of this definition depends on how well the elements of exterior orientation are known and on the relief of the ground. The use of this envelope, together with iteration and prediction techniques should allow an epipolar image to be produced without a DEM. This would then permit the use of any matching algorithm with SPOT data. An epipolar test image, resampled without using a DEM, has already been produced.

The system can be used to produce orthophotographs and stereo mates from single images with a DEM and from stereo pairs without a DEM by manual means and, when the current developments are complete, by automatic means also. Since it is possible to specify any sensible position for the ideal camera oblique views can also be produced, the ray tracing module will remove hidden lines and produce a perspective view. These techniques can be used for simulation of oblique imagery from SPOT or other sensors with the addition of suitable camera models and radiometric data.

6.0 Conclusions

The use of rigorous ray tracing techniques and a modular approach to programming has allowed a flexible system to be developed with a number of applications. Tests have shown the output to be accurate and suitable for the task in hand.

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8.0 References.

S.T. Banard and W.B. Thompson,
Disparity analysis of images,
IEEE trans. PAMI-2(4):333-340,1980.

T.K.W. Chau,
Specification and design for serial and parallel implementation of
the PMF stereo ranging algorithm in UCL-CS,
Alvey MMI-137 internal report, February 1987.

T.K.W Chau and G.P Otto,
The design and implementation notes for UCL-CS Gruens - A sheet growing
stereo matching algorithm,
Alvey MMI-137 internal report, January 1988.

K.A. Collins, A Anthony, J-P Muller and J.G.B. Roberts,
Transputer arrays for real-time feature point stereo matching,
Proc. ISPRS Conf. on fast processing of Photogrammetric data, Interlaken,
June 2-4, 1987.

I.J Dowman, The prospects of topographic mapping using SPOT data,
SPOT-1 conf. Image utilisation, assessment, and results,
Paris, France, 23-27 November, 1987.

I.J. Dowman, D.J. Gugan, J.P. Muller, M.A. O'Neill and V. Paramananda,
Digital processing of SPOT data,
Proc. ISPRS Conf. on fast processing of Photogrammetric data, Interlaken,
June 2-4, 1987.

T. Day and J.P. Muller,
Quality assessment of DEMs produced by automatic stereo matchers from SPOT image pairs.
To be presented, ISPRS conf. working group 3, Kyoto Japan, July 1988.

A.W Gruen and E Baltsavias,
Geometrically constrained multiphoto matching,
Proc. ISPRS Conf. on fast processing of Photogrammetric data, Interlaken, June 2-4, 1987.

D.J. Gugan,
Practical aspects of topographic mapping from SPOT imagery,
Photogrammetric record, 12(69): 349-355, 1987.

M. Landy and Y. Cohen,
The HIPL picture header standard,
Human Information Processing Laboratory, Psychology Dept,
New York University, 1982.

J.P. Muller, N. Dalton, A.C. Morris, V. Paramanda, A. Stevens,
Interactive map-image registration and automated feature extraction.
To be presented, ISPRS conf. working group 3, Kyoto Japan, July 1988.

M.A. O'Neill,
GPROC - An integrated system for the graphical processing of numerical data,
Software - Practice and Experience, 1987 (submitted).

G.P Otto,
Resampling SPOT data for stereo image matching,
Alvey MMI-137 internal report, October 1987.

S. Pollard, J. Mayhew, and J. Frisby,
PMF: A stereo correspondence algorithm using a disparity gradient limit,
Perception, 14:449-470,1985.

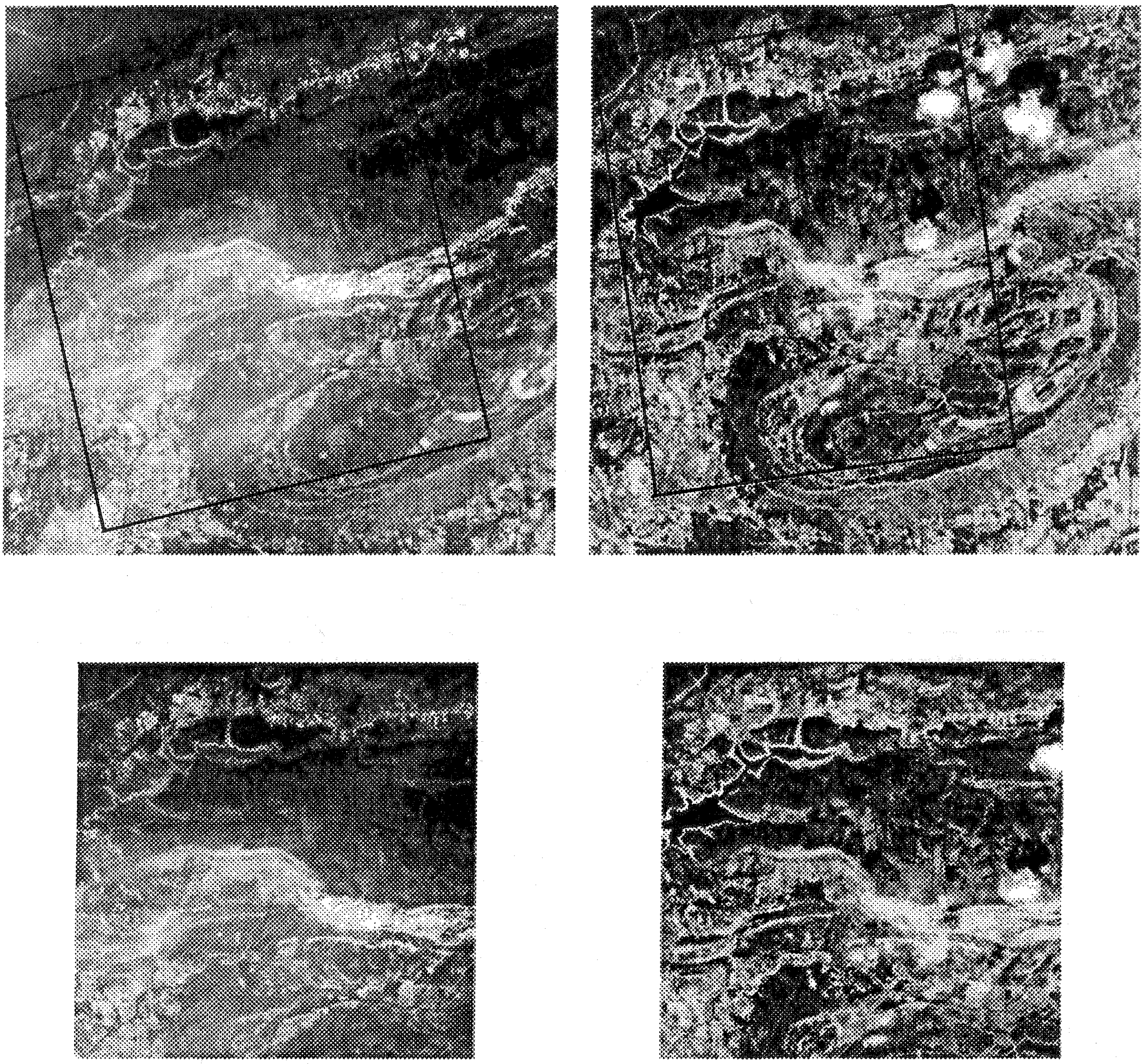


Figure 1. SPOT-1 (upper) and epipolar resampled (lower) stereo mates

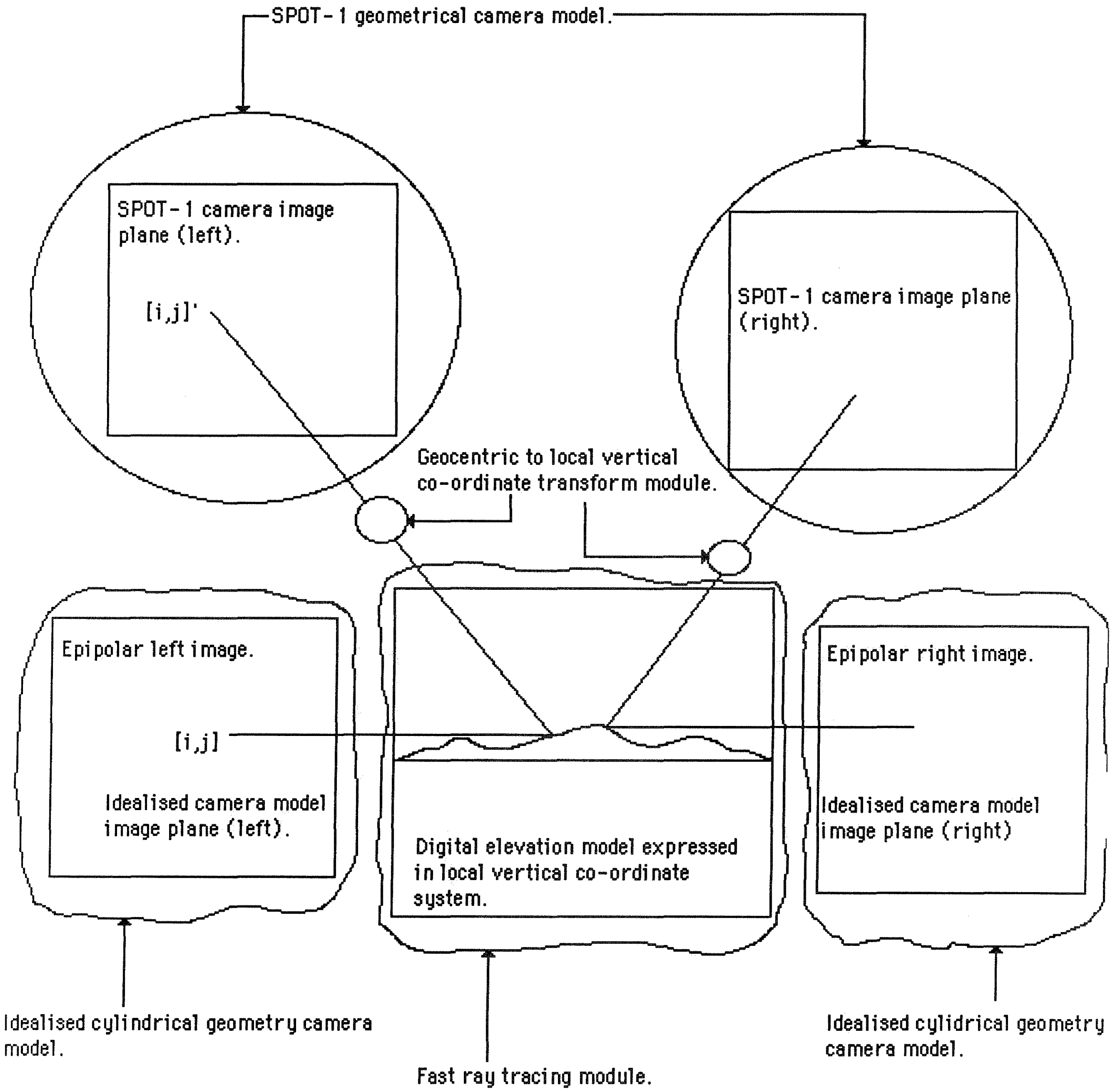
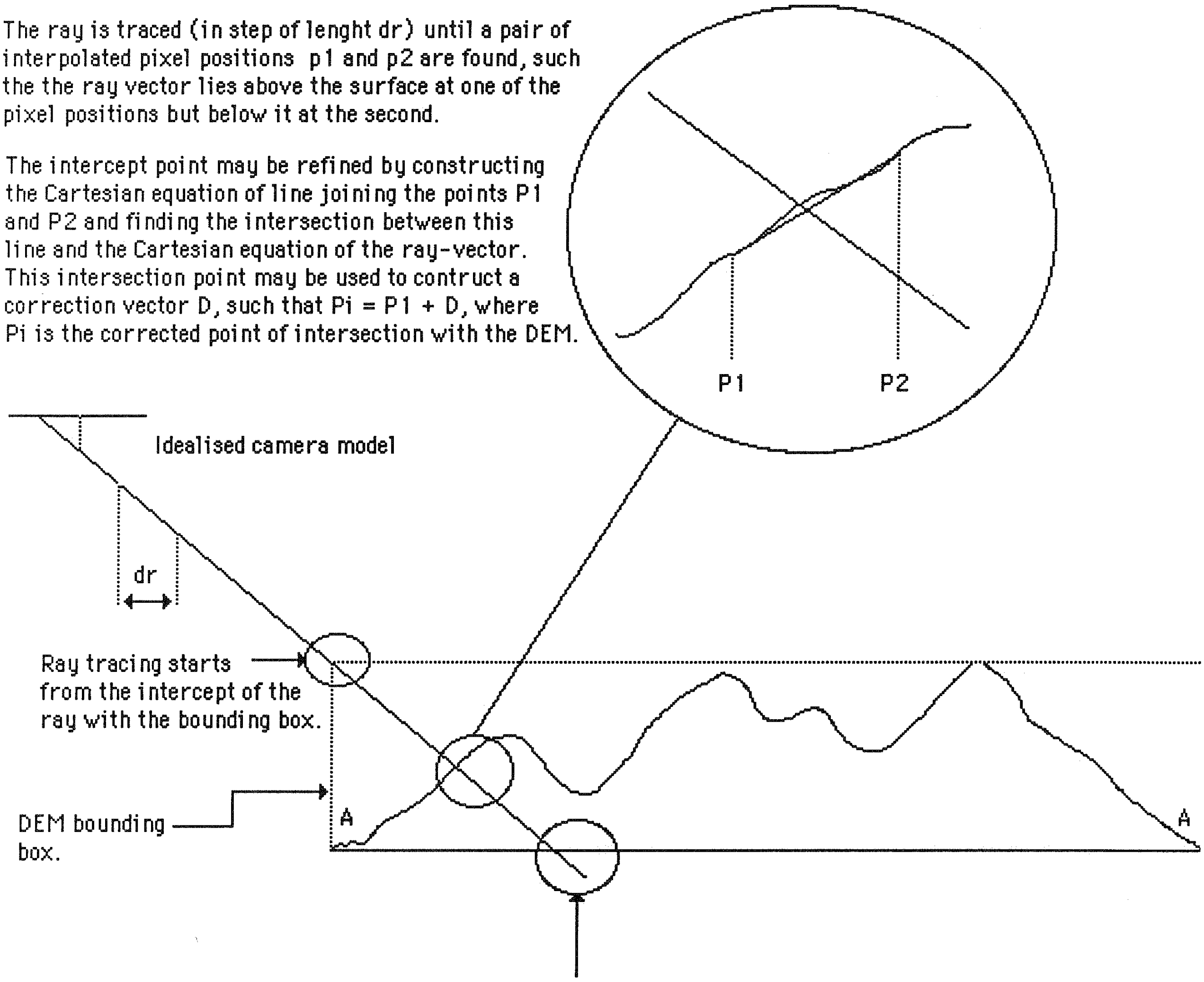


Figure 2. Schematic showing how the basic modules of the geometric camera module and their data dependencies.


The ray is traced (in step of lenght dr) until a pair of interpolated pixel positions p1 and p2 are found, such the the ray vector lies above the surface at one of the pixel positions but below it at the second.

The intercept point may be refined by constructing the Cartesian equation of line joining the points P1 and P2 and finding the intersection between this line and the Cartesian equation of the ray-vector. This intersection point may be used to contruct a correction vector D, such that Pi = P1 + D, where Pi is the corrected point of intersection with the DEM.

Ray tracing starts from the intercept of the ray with the bounding box.

DEM bounding box.

If the ray reaches the height datum without intersecting the DEM, or if it is outside the bounding box of the DEM, it is discarded.

Figure 3 b. Schematic showing the basis of the fast ray tracing technique.

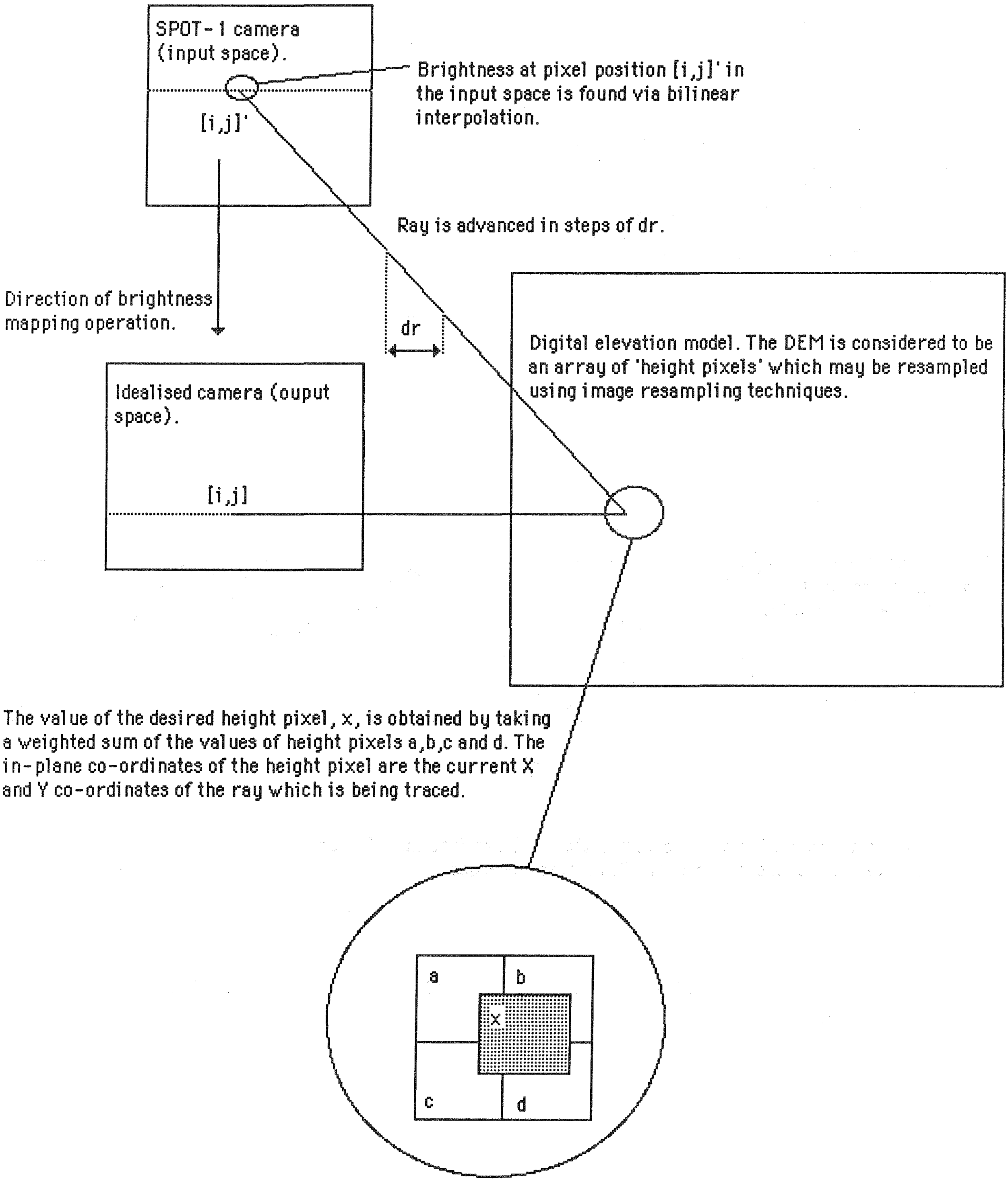


Figure 3a. Schematic of the fast ray tracing operation showing how height pixels are interpolated.