Topographic Mapping from SPOT Imagery

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ABSTRACT: Present day needs for medium and small scale topographic mapping at reduced cost can be met by using stereoscopic imagery acquired from the SPOT satellite.The non-conventional nature of SPOT imagery is reviewed and a geometrical model for image restitution implemented on analytical and digital stereoplotting instruments is described. This model gives accuracies compatible with mapping at 1:50,000 scale with 25-m contours. Considerable experience has been gained from working with SPOT data, and around 80 percent of the information content required by 1:50,000-scale mapping can be extracted. This figure can be reduced, however, if the imagery is affected by image degradation during film writing. Conclusions are drawn for the present and future utilization of SPOT data for mapping.

INTRODUCTION

THE 1980 United Nations survey on the status of world cartography, presented by Brandenberger and Ghosh (1985), reports that only 42 percent of the land area of the world (excluding Antarctica) is mapped at a scale greater than 1:125,000, and that of this area only 2 percent is revised each year. Maps at scales of 1:50,000 to 1:100,000 are widely regarded as a necessity for administration and development, yet this need is not being fulfilled by mapping operations in the world today. This situation can only realistically be improved by the adoption of different mapping strategies from those currently in use.

The Thematic Mapper instrument on Landsat 5 has been shown to have very high geometric fidelity (e.g., Welch *et al.*, 1985), but the imagery cannot be used to make accurate height measurements due to the low base/height ratio, and the information content of the data is not sufficient for mapping at 1:50,000 to 1:100,000-scale.

The Large Format Camera (LFC), flown on Space Shuttle mission STS 41-G in 1984 has a higher potential. Gruen and Spiess (1986) show that the geometric accuracy of the imagery is about 7.2 m in plan and 11.0 m in height, and that most of the information shown on the 1:100,000-scale map could be extracted. An experiment carried out by number of European photogrammetric organizations, however, tested LFC imagery under non-optimum conditions (OEEPE, 1987). Results showed that poor image reproduction seriously affected image interpretation and that standard photogrammetric control could not be used to give adequate accuracy. Until the Large Format Camera is scheduled to continuously acquire data with first generation photographic products distributed to end users, it cannot be considered as a practical source of map information.

The SPOT satellite, launched in February 1986, is able to acquire high resolution stereo imagery of almost all of the Earth's surface. This imagery is less costly and more easily obtained than aerial photography—imagery may be available within a few days if already acquired and archived. The purposes of this paper are to present a mathematical model of the geometry of linear array imagery, and to give results which assess the accuracy and completeness of medium-scale maps produced from SPOT imagery. The mathematical model has been implemented on two stereo plotting systems, one a Kern analytical stereo plotter, the other a digital photogrammetric system. Results from both of these systems are described. Details of the SPOT satellite system have been well reported in the literature (e.g., Rosso, 1978; Chevrel *et al.*, 1981) and will not be repeated here.

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THE NATURE OF DYNAMIC IMAGERY

The SPOT HRV panchromatic sensor has a linear array of 6000 detectors, each 13 μm in size. This array images a strip of the Earth's surface 60 km wide and 10 m long (each pixel corresponding to 10 m on the ground). A SPOT image is built up by combining 6000 of these linear strips, recorded every 1.5 ms as the satellite moves in orbit, resulting in a 6000 by 6000 pixel image.

A SPOT image is recorded over a 9-second period. As the position and orientation in space of the sensor are changing during this period, the image geometry is known as dynamic. An image has a parallel plane perspective (each linear strip having a two-dimensional plane perspective, an image being comprised of a series of approximately parallel planes) and cannot be treated in the same way as a normal frame photograph.

Early research into the geometry of dynamic images from aircraft mounted scanning instruments recognized the fact that not all of the conventional elements of exterior orientation ($x_S, y_S, z_S, \omega, \phi, \kappa$) can be determined (e.g., Case, 1967; Masry, 1969; Baker *et al.*, 1975). This was usually overcome by one of two methods—transforming the dynamic imagery into a series of "instantaneous equivalent frame photographs," or by obtaining some of the orientation parameters from auxiliary data.

A different approach has been used to model the geometry of dynamic imagery from Landsat (e.g, Bahr, 1978; Paderes and Mikhail, 1983). As the satellite is nominally pointing towards the center of the Earth, this method models the orbital parameters of the sensor during the period of image acquisition and obtains the six elements of exterior orientation from a number of these parameters (e.g., the true anomaly, orbit inclination, ascending node, and the radial distance). 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.

THE ORIENTATION OF SPOT IMAGERY

The orientation of SPOT imagery poses slightly different problems from that of Landsat imagery for a number of reasons: (a) The signficantly higher resolution of the panchromatic sensor allows higher accuracy geometric modeling, which should take into account all possible sources of image distortion; and (b) anything other than vertical imagery of relatively flat ground will contain measurable relief distortion, in which case it is necessary to use stereo imagery to obtain the maximum measurement accuracy (stereo imagery also results in significantly improved image interpretation).

Several different strategies have been adopted for the orientation of stereo SPOT imagery Guichard (1983) describes a method which considers all orbital perturbations acting on the satellite

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as a scene is imaged, including the high frequency rates of change of attitude recorded by the satellite attitude measurement system.

Kruck and Lohmann (1986) have a different approach whereby the dynamic images are orientated by a modified conventional bundle adjustment program. The modifications allow for the orbital motion of the satellite, eight predicted image distortions (such as Earth rotation and curvature), and up to 24 additional parameters.

The orientation of SPOT imagery is also a component of the MacDonald Detwiller Associates (MDA) Meridian mapping system. Friedmann *et al.* (1983) describe the geometric approach used by MDA for Landsat image geometric correction.

The orientation method adopted for the software suite described in this paper is essentially similar to that independently developed by Salamonowicz (1986). It has been found that this approach gives adequate accuracy for SPOT imagery on the basis of suitable mapping scales for the image information content, while requiring no external information and relatively small amounts of ground control.

The exterior orientation of the SPOT imagery can be modeled by consideration of the eulerian elliptical orbital parameters, shown in Figure 1. For SPOT, two of the six orbital parameters have very little effect on the image geometry. These are the semi-minor axis of the orbit ellipse (b), and the argument of the perigee (ω) due to the very low orbit eccentricity (e).

The major components of the dynamic motion are well known-the movements of the satellite along the orbit path, and the rotation of the Earth. The two parameters affected by these motions, the true anomaly (F) and the ascending node (Ω), are modeled by linear angular changes with time (obtained from the orbit period and the Earth rotation rate):

$$F = F_0 + F_1 x$$

$$\Omega = \Omega_0 + \Omega_1 x$$

where x = the along track image coordinate, the only measure of time available.

The sensor attitude (defined by the orthogonal rotation matrix $\mathbf{R}_0$) and position in space ($\mathbf{X}_S$) with respect to the geocentric coordinate system can be found from these orbital parameters:

$\mathbf{R}_0 = \mathbf{R}_{\Omega'}\, \mathbf{R}_{i'}, \mathbf{R}_{F'}$ (rotation between sensor and geocentric coordinate systems)

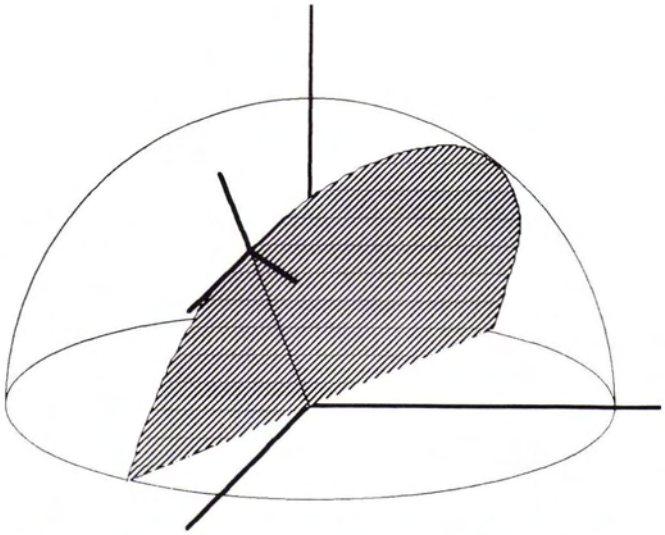

FIG. 1. SPOT sensor geometry modeled by orbit parameters.

$\mathbf{X}_s = \mathbf{R}_0\mathbf{D}$ (perspective center position in space)

where $\Omega' = 180° - \Omega$
$i' = i - 90°$
$F' = 90° - (F + \omega)$
$\mathbf{D} = (0, 0, r)^T$
$r = a(1 - e^2)/(1 + e \cos F)$
i = orbit inclination
a = orbit semi-major axis

The unknowns in the collinearity equations ($\mathbf{X}_S$ and $\mathbf{R}_0$) are now expressed in terms of four unknowns (F_0, Ω_0, i, a) and can be found by means of a space resection; i.e.,

$$(0, y, -f)^T = s\mathbf{R}_0(\mathbf{X}_A - \mathbf{X}_S) \text{ where } s = \text{scale factor.}$$

Using this method, the exterior orientation of an image can be found with as few as two ground control points. The accuracy of this orientation is not particularly high, however, as the satellite is not pointing precisely towards the center of the Earth. The space resection orientation is therefore extended to allow additional sensor attitude rotations (defined by an orthogonal rotation matrix $\mathbf{R}_A$). The collinearity equations now become

$$(0, y, -f)^T = s\mathbf{R}_A\mathbf{R}_0(\mathbf{X}_A - \mathbf{X}_s)$$

A further extension allows linear angular rates of change with time (drift rates) to be included in the attitude rotation matrix. These parameters will account for almost all of the dynamic motion of the sensor. The only external information (other than control point coordinates) required by the orientation program is the viewing angle of the sensor for each image, and this is easily obtained from the *SPOT Image* on-line database.

THE REAL-TIME LOOP

A SPOT image does not have the central perspective geometry of a photograph, so an analytical plotter is required to mathematically create a stereo model. The real-time loop is the computer program that continually uses the collinearity equations to calculate image positions corresponding to the currently defined model position and drives the stage plates to these positions. One method which has been adopted by some organizations (e.g., Konecny *et al.*, 1987) for dynamic SPOT imagery is to use the normal central perspective real-time loop and to use dense look-up tables to correct the image distortion. As these corrections are applied to the image coordinates, at least two look-up tables are required for a range of ground height values. The look-up table interpolation is a relatively time intensive task and is normally run as a separate process to the real-time loop. This approach is most applicable to analytical plotters with a single processor and a large CPU memory, when the speed of the real-time loop is critical and would normally be written in assembly language.

The alternative method adopted at University College London for the geometric model described above is to incorporate the inverse collinearity equations for the dynamic SPOT imagery in the real-time loop. As the orientation parameters are a function of the along track (x) coordinate (initially unknown), the equations transforming an XYZ model coordinate onto the image plane are necessarily iterative. Whereas the inverse equations for a frame photograph require 24 computer multiplications to transform model coordinates to image coordinates, the same process for the SPOT model requires around 330 computer multiplications. This method is advantageous when (a) the real-time loop is computed by a separate processor, or (b) when there are CPU memory restrictions on the size of the real-time loop program. A separate processor is usually powerful enough to compute the equations in real-time (50 cycles per second), but may not have the memory capacity to hold dense look-up tables.

THE KERN DSR SPOT SOFTWARE SUITE

The geometric and real-time loop programs described above have been implemented on the Kern DSR analytical stereoplotting system. Much of the software necessary to utilize SPOT imagery is already available for most analytical plotting systems, such as inner orientation, image measurement, and data collection. After the image coordinates of a number of ground control points have been measured, the SPOT orientation program is run to compute the dynamic orbital exterior orientation parameters. These are downloaded to the SPOT specific plate processor program which uses the parameters to continuously compute the transformation between the model and image coordinate systems. As SPOT imagery covers a large area, the model coordinate system used is the geographic system (latitude, longitude, and height). These computations can be handled sufficiently fast by the standard LSI 11/23 real-time loop processor. Scanning the model in the Universal Transverse Mercator (UTM) map projection system places an extra burden on the real-time loop (the UTM to geographic transformation) and requires a faster processor (LSI 11/73).

The standard map data collection programs can be used with the SPOT model, and off-line map projection transformation programs are available if the data are recorded in the geographic coordinate system.

The orientation and real-time loop software has also been implemented on the Wild Aviolyt ACI, BC1, BC2 analytical plotters by Aviosoft, Switzerland. This implementation uses the inverse collinearity equations to create a 25 by 25 point image space deformation grid, subsequently used with the standard central perspective program for the real-time loop.

THE GEMS DIGITAL STEREOPLOTTING SYSTEM

Film based stereoplotting systems suffer from one major disadvantage—image degradation during film writing process. Figures 2 and 3 show the image quality of digitally displayed SPOT imagery and an average quality film product. For this reason a completely digital stereoplotting system for SPOT was developed at University College London based on an I²S Model 75 image processor (Gugan and Dowman, 1986).

A fully developed digital stereoplotting system and a digital mapping operation has a number of advantages-low cost hardware, automatic image handling, and integration of most mapping processes (image enhancement, automatic digital terrain model generation, digital data superimposition and editing, automatic ortho image generation, digital map drafting).

The I²S system has now been ported onto the GEMS of Cambridge GEMSYS 35 Image processor. The heart of the GEMSYS 35 is the Motorola MC68020 display processor. This runs all image handling programs and can have up to 256 Mb of random access image memory. This can be reconfigured in any way to store imagery and graphics. Four zoom/pan controllers can be linked to any number of image/graphics planes. The high resolution display has 1480 by 1024 pixel resolution.

The SPOT software is organized in the same way as on the Kern system—image coordinates are measured using a stereo comparator program, the orientation program computes the exterior orientations of the two images, and these parameters are used to create the stereo model. The two images are displayed in split screen mode and a mirror stereoscope device mounted in front of the display is used for stereo viewing. The stereo model is controlled with a mouse for *XY* movements and two continuously sampled buttons for +/− height. Map data and digital terrain models can be recorded in the same way as with conventional stereoplotters. Map data can also be superimposed in stereo on the model and edited.

Development is continuing with this system, to implement a full range of photogrammetric software and to automate a number of the processes. An array of inmos Transputer chips can be linked to the display processor, and this is being programmed for automatic image correlation purposes.

SPOT-1 IMAGERY

SPOT-1 was launched on 22 February 1986, and since then has been transmitting back to ground stations high quality imagery of the Earth. SPOT imagery can be obtained in a variety of formats suitable for mapping applications

1A: This level of data is corrected only for sensor radiometric calibration. As the data are un-resampled they have the maximum possible information content.

1B: Level 1B data is additionally corrected for known geometric distortions, including Earth rotation, Earth curvature, sensor viewing angle, and satellite attitude variations. As the SPOT geometric model described above corrects for these distortions, no advantage is gained from using this level for photogrammetric applications, and the image quality will be degraded somewhat by resampling.

1P : Level 1P (for Photogrammetric) data is basically a level 1A image with geometric correction for high frequency attitude variations. As the SPOT model does not correct for these distortions, this product should give superior accuracy. However, in an area of one image evaluated, the image correction resulted in under-sampling. Subsequent resampling created pixels with a ground size of about 30m. This seriously degraded image interpretation potential.

The photogrammetric software suites described above are designed to use geometrically uncorrected level 1A imagery, all necessary corrections being applied mathematically to image and ground coordinates. The 1P product can also be used as the corrections applied for this level are not included in the orientation algorithm.

Image quality is of particular importance for mapping applications. Welch (1982) shows that a 10-m instantaneous field-of-view (IFOV) is a critical size for the completeness of map detail extraction, and any effective degradation of the SPOT IFOV is clearly highly undesireable.

Digital SPOT image data contains a tremendous amount of information both as subtle grey level values and as high frequency linear features, often less than 1 pixel in width. However, it is noticeable that a significant degree of image degradation occurs during the process of film writing. Two main factors influence the photographic image quality—the transfer of the maximum grey scale range onto film, and the preservation of the high frequency information. The first process relies on the histogram of the digital data being matched to the sensitivity range of the photographic film The second process relies on adjacent pixels in the image being printed with different digital values. Laser film writers are superior for high frequency detail, clearly printing individual pixels. Continuously modulated LED film writers are better for the reproduction of subtle radiometric variations, preserving image texture. For the linear feature following predominant in topographic mapping applications, the preservation of the high frequency information was found to be more desirable than radiometric fidelity (if a choice had to be made), although the measurement of aerial features such as digital terrain models is probably better when the image texture is preserved.

STEREO MODEL ACCURACY

As a part of the Preliminary Evaluation Programme for SPOT (PEPS),the area around Aix-en-Provence, southern France (scene 50-262) has been evaluated from stereo model accuracy and image interpretation. Three level 1A images, acquired on 12 May 1986, 18 May 1986, and 1 June 1986 were used (mirror angles of 3.00°, 22.6°, and −17.5°).

Ten photogrammetrically or geodetically derived ground control points were used for image orientation and 20 check points measured from the 1:25,000-scale map sheets were used to check

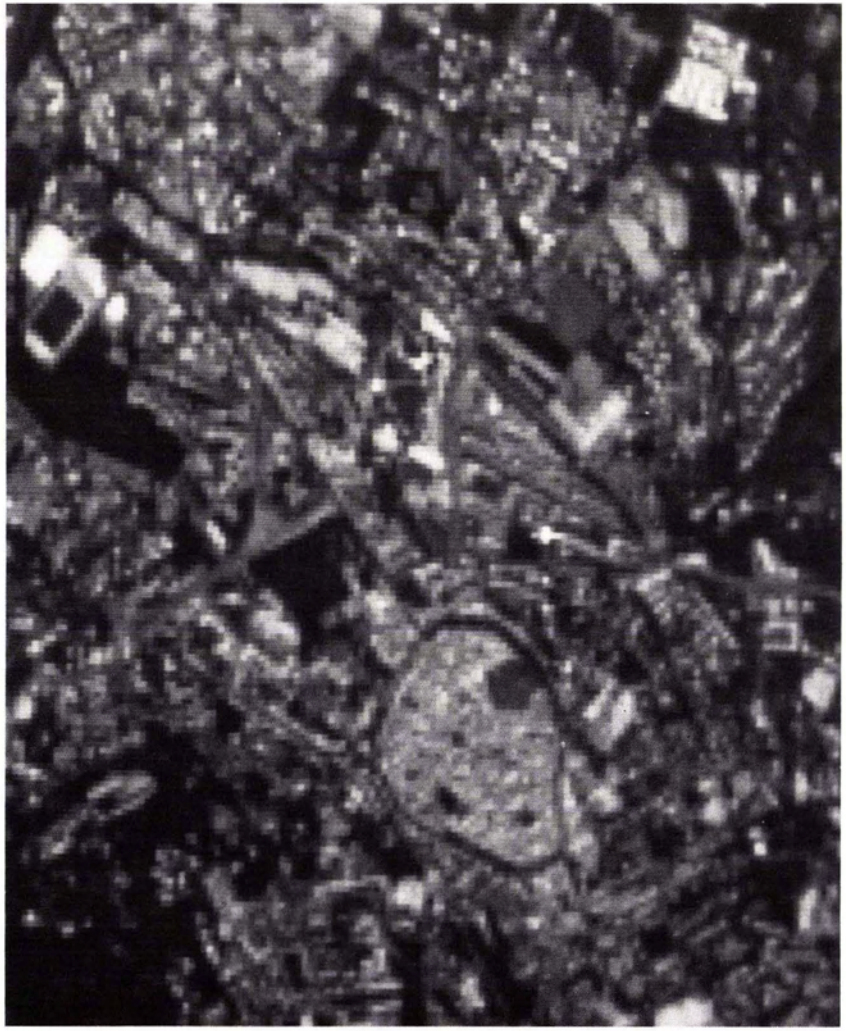

FIG. 2. SPOT image of the town of Manosque photographed from the screen of the I^2S image processing systems. SPOT image Copyright 1986 CNES.

FIG. 3. SPOT image of the town of Manosque taken from a copy of the film product supplied by SPOT image. SPOT image Copyright 1986 CNES.

the model. An additional 42 spot heights were taken from the 1:25,000-scale maps to check heights. Control and check points were well distributed over the whole model. A selection of results are given below:

Ten control points used for orientation:

RMS Plan Accuracy (20 check points):	17.7 m
RMS Height Accuracy (62 check points, $B/H = 0.73$):	5.4 m
RMS Height Accuracy (53 check points, $B/H = 0.32$):	8.0 m

Six control points used for orientation:

RMS Plan Accuracy (20 check points):	17.7 m
RMS Height Accuracy (62 check points, $B/H = 0.73$):	5.9 m

Two level 1P images have also been measured. These images (scene 50–262) were acquired on 22 March 1986 and 11 May 1986 (mirror angles of 26.2° and −22.3°). Control was not available over the whole stereo model, however.

Eight control points used for orientation:

RMS Plan Accuracy (18 check points):	13.1 m
RMS Height Accuracy (62 check points, $B/H = 0.73$):	7.4 m

A second sterescopic pair of SPOT images over the United Kingdom has also been used to check accuracy. The scene is 029-242, covered by images dated 17 and 24 April 1987 with mirror angles of −18.6 and 17.4 degrees. A large number of control points with an accuracy of about 1m in *X*, *Y*, and *Z*, were provided by the Ordnance Survey. The model was oriented with ten ground control points for each image and 17 check points were used to assess accuracy. The mathematical model used was refined to test this data to make use of the attitude data provided in the SPOT header file. The results indicate that high frequency rates of change of attitude can be used to improve the overall accuracy of the stereo model, but, more importantly, that improved accuracy can be obtained by the use of high quality ground control data.

RMS error from UK pair with ten control points on 17 check points

	Plan	Z	Plan	Z
No attitude data	8.8 m	7.4 m	8.7 m	10.2 m
(10 parameters)	(7 parameters)			
With attitude data	8.3 m	7.4 m	8.4 m	10.1 m
(10 parameters)	(7 parameters)			

Points measured during image orientation have been shown in several tests to be less acurate than when measured in the stereo model. This is particularly significant in height measurement which is very delicate with SPOT imagery. The heights of 71 well defined spot heights were therefore measured in the stereo model set up with ten parameters and no attitude data; a root-mean-square error of 3.6 m was obtained.

IMAGE INFORMATION CONTENT

The ease of extraction of map detail from SPOT imagery somewhere between that of small scale aerial photography and Landsat TM imagery. Many features are not directly identifiable on the imagery but their presence is inferred by the context of their surroundings—roads, streams, buildings, etc., can be indicated by discontinuity of the surrounding land use. Interpretation of SPOT imagery is, therefore, heavily dependent on the skill and experience of the interpreter, and his familiarity with the landscape.

A number of factors influence the completeness of map detail extraction.

- Image quality, if film imagery is used.
- Sensor look angle. The most difficult areas to map are high frequency urban areas, and it was found that the road network was less well interpreted with oblique imagery than with vertical imagery, as high buildings obscure the linear detail. To extract the maximum amount of information, it was necessary to use the digital plotting system with its optimum image quality.
- Use of multispectral data. One particular problem encountered mapping urban areas with SPOT is the discrimination of vegetated areas within the urban environment. Chavez (1986) describes the digital merging of Landsat TM data with higher resolution panchromatic imagery, and Cliche *et al.* (1985) describe the integration of SPOT multispectral and panchromatic imagery. Both of these studies show the improved land-use discrimination obtained from use of the multispectral information. The digital plotting system is particularly suited to the integration of data types for this purpose.

In order to test the completeness of map detail that can be extracted from SPOT stereo imagery, plots were produced at 1:50,000-scale on the Kern DSR and I²S digital plotter. A full report of work on this topic is given by Dowman and Peacegood (1988). A summary of results is given in Table 1.

CONCLUSIONS.

This paper has been concerned with the methods of map compilation from SPOT imagery and the accuracy attainable. A brief mention has also been made of image content. It is quite clear that SPOT data can be used in an analytical stereo plotter or a digital stereo plotter with the same facility as aerial photographs. The software used for the tests performed here is available for Kern DSR and Wild Aviolyt analytical plotters and the GEMS digital stereoplotting system. Different SPOT software packages are available for most other photogrammetric analytical plotters.

The accuracy and completeness evaluation reported in this paper indicate that SPOT is a potential source of imagery for 1:50,000 and smaller scale mapping tasks. Plan accuracy of >=20m and height accuracy of >=8m is suitable for these scales, and a majority of the information required can be extracted, albeit with an increase in field completion. Although data have not been as readily available as was expected, this situation is improving, and Rochon and Toutin (1986) consider mapping of large areas with SPOT to give considerable savings over conventional methods.

SPOT imagery contains a wealth of information that can be utilized to its optimum for map revision purposes, when image interpretation is less important than the recognition of ares of change. Change detection could be optimized for medium scales by digital data superimposition. The large area covered by each SPOT image would speed this process considerably. Stereo plotting could be used to update the map data immediately, provided no degradation of the map accuracy occurred.

In conclusion, SPOT can be considered as a realistic alternative to very high altitude aerial photography for mapping at medium and small scales.

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TABLE 1. RESULTS OF PLOTTING ON KERN DSR1 DERIVED FROM A COMPARISON WITH PLOT AND 1:50000-SCALE MAP

Feature	Percent correctly plotted
Roads (major)	87
Canals (major)	100
Rivers	100
Railways	97
Residential buildings	67
Industrial buildings	(many changes which could not be checked)
Minor roads/tracks	24
Canals (minor)	0
Streams	55

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