Evaluation of the Stereoscopic Accuracy of the SPOT Satellite

V. Rodriguez, P. Gigord, A. C. de Gaujac, and *P. Munier*
Institut Géographique National, Toulouse Space Centre, 18 Avenue Ed. Belin, 31055 Toulouse, France
G. Begni
Centre National d'Etudes Spatiales, 18 Avenue Ed. Belin, 31055 Toulouse, France

ABSTRACT: The SPOT-1 in-flight assessment period for restitution of terrain relief took place from March to November 1986 under the direction of the French Institut Géographique National (IGN). For this purpose, two test regions in the south of France were chosen, and ground control points and check points were selected in these regions before launch of the SPOT satellite. The following process was used:

- Plotting of ground control points, and modeling of SPOT viewing geometry;
- Plotting of check points, and calculation of their restituted positions; and
- Calculation of deviations from the real positions.

These operations were performed on a TRASTER/MATRA analytical stereoplotter using SPOT software compiled by the IGN. The analysis of the results shows that the specifications have been reasonably well met, with restitution accuracies always under 10 metres in planimetry and 7 metres in elevation. This fulfills the cartographers' expectations regarding SPOT (Baudoin, 1983), and gives some idea of the extent to which SPOT will be contributing to the future evolution of photogrammetry and cartography.

INTRODUCTION

THE IN-FLIGHT ASSESSMENT of the SPOT 1 satellite by the Centre National d'Etudes Spatiales (CNES) began with the transmission of the first image in February 1986, and was largely completed by April 1986 (radiometric aspects, and certain geometric aspects related to instrument bias) (Begni *et al.*, 1985).

The last phase of the in-flight assessment, the objective of which was to validate the SPOT's stereoscopic acuteness, lasted until November 1986. This was conducted under the direction of the French Institut Géographique National (IGN) by a team from the IGN working at CNES-Toulouse as part of a cooperative scheme between these two agencies. Measurements were carried out on a TRASTER/MATRA stereoplotter at the IGN, St. Mandé.

The aim of this paper is to describe the methods used for assessment, the sequence of operations, and all the results obtained. During the checkout, SPOT's stereoscopic acuteness was tested using a set of ground check points. This paper continues with consideration of the wider perspective concerning the photogrammetric exploitation of SPOT images, and presents studies currently underway at IGN directed towards a new operational environment.

CHECKOUT METHODS AND SEQUENCE OF OPERATIONS

NOTES CONCERNING SPOT 1 VIEWING

SPOT 1 is a push-broom sensor system in a circular heliosynchronous orbit (altitude 832km, 517 miles) which repeats its coverage every 26 days. Its payload includes two identical optical instruments, the HRV1 and HRV2 (High Visible Resolution). It produces images in two modes:

- Panchromatic mode (P), with a single spectral band ranging from 0.51 μm to 0.73 μm, and a ground resolution of 10 metres; and
- Multispectral mode (XS), with three spectral bands (band 1: 0.50 μm to 0.59 μm; band 2: 0.61 μm to 0.68 μm; and band 3: 0.79 μm to 0.89 μm), and a ground resolution of 20 metres.

For each spectral band, the radiance picked up by the optical system is measured by an array of CCD detectors (6000 for the P mode, 3000 for each of the spectral bands of the XS mode) which forms rows of the image perpendicular to the satellite track.

The acquisition of the image in the column direction (parallel to the satellite track) is achieved by movement of the satellite in its orbit (push-broom system), as indicated in Figure 1. The scenes so obtained cover a surface area of 60 km by 60 km (37 miles by 37 miles). A 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 ground at different look angles (including oblique viewing) from different orbits in order to record a pair of stereoscopic images (see Figures 2 and 3).

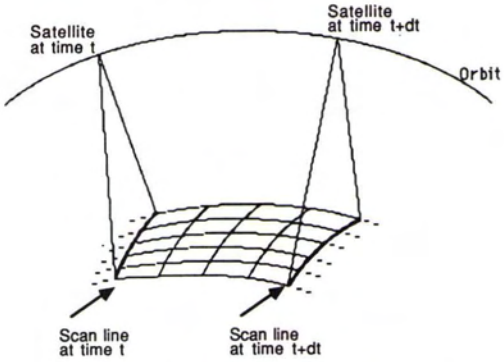

FIG. 1. Acquisition of a SPOT scene.

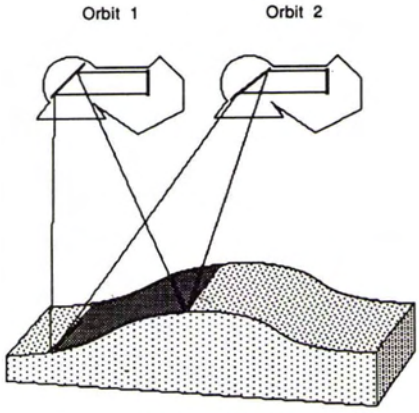

FIG. 2. Stereopair of a SPOT scene.

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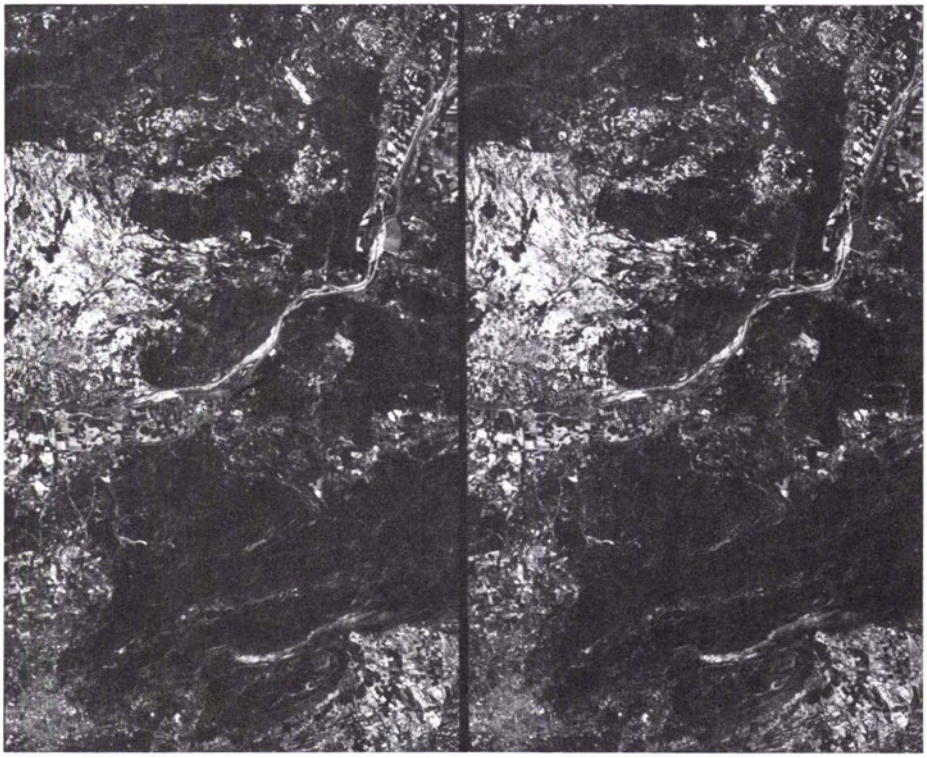

FIG. 3. A stereogram of the Aix-en-Provence region of France. The right scene was taken on 11 May 1986 with an incidence angle (angle from nadir) of 25.0° to the left. The left scene was taken on 12 May 1986 with an incidence angle of 3.4° to the right. © SPOT image Copyright 1986 CNES.

The classical photogrammetric base-height ratio (*B/H*) can be defined in that case as the ratio of the distance between the two orbits to the altitude of the satellite.

CHECKOUT ORGANIZATION

For the purposes of stereoscopic evaluation of the SPOT 1 satellite, the analysis was based on a set of restituted coordinates, plotted from the images, for points whose exact positions were already known. The checkout sequence, then, was as follows:

- Determination on the ground of a set of points making up a control network;
- Programming the acquisition of SPOT imagery over the predefined geographical areas;
- Development of restitution software modeling the SPOT acquisition geometry;
- Processing the stereopairs utilizing ground control points (GCP), then plotting check points (CP) and determining their restituted coordinates; and
- Analysis of the results.

DETERMINATION OF A NETWORK OF CONTROL POINTS

Some 177 points were identified on aerial photographs covering the two selected geographic regions, i.e., about one point per 10- by 10-km area. Coordinates of these points, defined with accuracies under 3 metres in the *X,Y* plane and under 1.5 metres in *Z*, were determined by the Photogrammetry Service of the IGN in July of 1985.

IMAGE ACQUISITION PROGRAMMING

Three configurations of the two scenes making up a stereopair were taken:

Incidence angle for Scene 1	+ 27°,	Scene 2	− 27°
Incidence angle for Scene 1	+ 0°,	Scene 2	± 27°
Incidence angle for Scene 1	+ 13°,	Scene 2	− 13°

Because of the short acquisition period available for the in-flight assessment (March through May 1986), and in order to obtain a large enough number of sufficiently independent stereopairs, an optimization had to be made of the programming possibilities available. This was done by means of software able to calculate the various possibilities for images, and evaluate the eventual consequences of these choices in terms of final equipment in SPOT scenes and stereopairs.

Thirty-one correct scenes were obtained. They are shown in Table 1, which lists for each scene the incidence angle, which HRV instrument was used, and the mode (panchromatic or multispectral). Sixty stereopairs were formed from combinations of these scenes, with the possibility of each scene being used in more than one stereopair.

14 stereopairs, +27°/−27°, $B/H = 1$
42 stereopairs, 0°/±27°, $B/H = 0.5$
4 stereopairs, +13°/−13°, $B/H = 0.5$

PROCESSING OF STEREOPAIRS

The stereopairs were processed using the IGN's TRASTER/MATRA stereoplotter. The IGN's TRASTER software, developed for use with aerial photography, was adapted to handle SPOT images (i.e.,

TABLE 1. SCENES ACHIEVED FOR SPOT'S STEREOSCOPIC IN-FLIGHT ASSESSMENT

HRV n° mode	incidence angle	Number of scenes				
		+27°	−27°	0°	+13°	−13°
HRV1	P	3	4	3	1	1
	XS	0	1	1	0	0
HRV2	P	3	3	3	2	3
	XS	0	1	2	0	0
		6	9	9	3	4

different sensor geometry, and introduction of data on satellite orbit and attitude).

Restitution was carried out using standard negative films,—with radiometric preprocessing but raw geometry—at a scale of 1:400,000. Both of each stereopair's scenes were treated simultaneously to obtain two correspondences (see Figure 4); that is,

$$C_{\text{Left}} \quad : \quad (l_L, p_L) \quad --- > \quad (s_L, \vec{u}_L)$$

$$C_{\text{Right}} \quad : \quad (l_R, p_R) \quad --- > \quad (s_R, \vec{u}_R)$$

where (l, p) are image coordinates,

s is the position of the viewing point corresponding to the instant that line l was exposed (for the negative in question), and

$\vec{u}$ is the look direction corresponding to pixel p at the instant that line l was exposed.

The formulation of each viewing system is a physical modeling which is directly inspired from the models used in aerial photogrammetry using nine parameters.

Simultaneously taking into account the ephemeris and the attitude rate gives at every instant the approximate position of the satellite and the orientation of the viewing instrument. Changes in satellite position are assumed to be linearly dependent on time (six parameters), while changes in orientation are assumed to be constant (three parameters).

A least-squares adjustment of the 18 parameters needed for modeling the geometry of a stereomodel can be performed employing stereoplotted measurements of ground control points and homologous points (pass points, which give only two pairs of image coordinates, but with unknown ground coordinates). The adjusted correspondences are dependent, therefore, on the distribution of the points used and the accuracy of measurements.

The advantages of this type of modeling are

- the same Ground Control Points are used for modeling both views of the same stereopair; and
- the modeling tends to minimize the distance between the two homologous look directions, minimizing at the same time the distance between these two look directions and the real position of the corresponding point on the ground.

The remaining residuals (planimetric, altimetric, and parallax) are the result of residual errors related to

- approximate formulation of the viewing system geometry,
- errors in the determination of image coordinates for the ground control points,
- errors in the ground coordinates for these ground control points, and
- possible errors in plotting the homologous points.

Because of these errors, the computed left and right look directions don't intersect. Figure 5 shows what happens. Practically, six to ten points (GPCs) from the control network were sufficient to establish the model with all the remaining points (CPs) visible on each stereopair being then used for restitution plotting.

Seventy-one restitutions gave 1621 stereoscopic plots (561 GCPs and 653 CPs), with 95 points used in the control network.

The results were given to the analysis unit in the form of listings including

- the characterization of scenes making up the stereopair,
- the plate measurements for each GCP and CP, and
- the residuals found for each GCP and CP.

RESULTS

Analysis of Results

The results were analyzed in several stages:

- Estimation of the errors in identification and measurement on film of the control network points (examination of the "plate coordinates"),
- Estimation of the modeling quality (examination of the residuals for ground control points), and
- Estimation of the restitution quality (examination of the residuals for check points).

Quality of Plotting

The purpose of this investigation was to observe and quantify the dispersion around a central position of measurements of the same point on the same film negative. Deviations observed may be the result of plotting errors or incorrect calculation of the transformation (x, y) TRASTER --> (l, p) image. Allowance, in the form of film distortion bias, has been made for the latter error (an error in the measurement of fiducial marks), but substantial deviations are still present as a result of identification problems related to the use of negative films, absolute orientation of the stereomodel, and differences in aspect of the same detail between the two stereopair images. All points may be subdivided into three categories:

Category 1:

- Dispersion between 1 and 5 m.
- Points correctly defined on the terrain and clearly identifiable on the film negative.

Category 2:

- Dispersion between 5 and 10 m.
- Points correctly defined, but with plotting on the film negative slightly out or not well defined.

Category 3:

- Dispersion greater than 10 m.
- Points poorly defined, or virtually invisible on at least one image.

During this investigation, neither the spectral mode (P or XS) nor the viewing incidence angle were seen to have any effect on the quality of plotting.

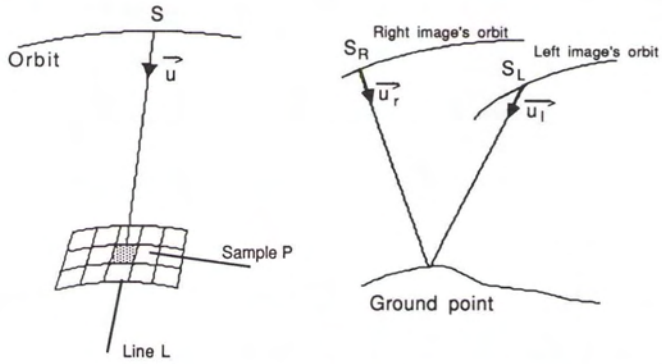

FIG. 4. (a) Correspondence characterizing each taking view. (b) Homologous look directions.

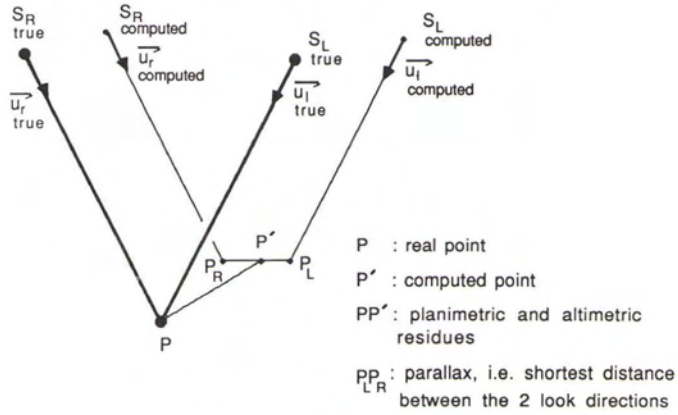

FIG. 5. Plotting of a point.

Quality of Modeling

The analysis of the modeling residuals found for each of the 73 points used as GCPs shows that points fall into three categories.

1 : Points with correct ground coordinates, and clearly identifiable on the plate (excellent quality plotting);
2 : Points with probably correct ground coordinates, but with only approximate identification; and
3 : Points with mean plotted position not corresponding to the ground coordinates. The interpretation may be systematically false, unless the ground coordinates are false.

The RMS of modeling residuals over all 561 measurements was 4.5 m in X and 4.1 m in Y and Z.

More generally, it may be said that

- Six to eight GCPs are sufficient to obtain a reliable modeling, and
- the residual values obtained for the stereopairs ($+27°/-27°$, $B/H=1$) are significantly lower than for the other stereopairs ($B/H=0.5$). This probably owes something to the convenience of the plotting (exaggerated relief and non-tilted stereomodel, as occurred with the $0°/+27°$ configuration).

Finally, it can be seen that the RMS residuals for ground control points are, for each modeling, almost all less than 6 meters, for whatever the number of GCPs, the base/height ratio (B/H), the geographic area, and the spectral mode.

Restitution Quality

The restitution residuals obtained for the check points (which did not appear in the calculations for forming the model) provided the sole data for acquiring an objective assessment of SPOT's stereoscopic performance. These residuals are, however, dependent on the quality of the corresponding modeling, on the errors committed in plotting the CP, and on the errors in determining the CP ground coordinates.

Eighty-six points were used as check points. The very high residuals found for four of these revealed large errors of interpretation, and these four points were eliminated during subsequent analysis. The RMS residuals obtained for the 631 remaining measurements were 8.0 m in X, 6.6 m in Y, 7.1 m in Z, and 4.6 m in P (parallax).

Examination of the residuals for each CP shows a higher degree of dispersion than for the GCPs. Indeed, modeling requires a certain level of consistency between GCPs, whereas the measurements performed on CPs are directly used to estimate the position of a point on the ground, and this estimate may differ substantially from the real position. Furthermore, it can be seen that very high mean and maximum residuals for check points can be observed for too many modelings. This means that the data for analysis must be filtered so as not to charge the SPOT system with a degradation of its stereoscopic qualities that is, in fact, simply the result of taking into account plottings which are clearly incorrect.

Two filtering methods were applied independently from each other. This was done by establishing a coherent kernel of residuals (with respect to the limit mean $\pm 2.7\sigma$), either for each modeling or for all measurements. The results obtained for both methods correlate very well, and are given in Table 2.

Generally speaking, it can be said that RMS residuals of less than 6 m are obtained when at least eight GCPs are used for constitution of the model.

Table 2. Filtered Residues Obtained on Check Points

	RMS of residuals			
	X	Y	Z	P
filtering per modeling	4.8 m	4.5 m	5.3 m	4.2 m
overall filtering	4.6 m	4.4 m	5.3 m	4.1 m

The quality of the images seems to be of great importance; the results obtained for the southerly region, where the image quality is excellent, are all clearly better that those obtained for the other regions (snowy or cloudy images).

Special emphasis was given to examining the effect of the B/H ratio on the restitution quality. Table 3 shows this to have an important bearing, particularly in Z. The uniform degradation in residuals for $B/H = 0.5$ can be explained by the difficulties in stereoscopic observation existing for the $0/\pm 27°$ configuration. Indeed, the fact that the two incidence angles are not symetrical about the vertical produces a tilted stereomodel. In addition, the perspective effect existing for oblique viewing leads to "x" plate scale differing by about 30 percent. On the other hand, using a simple model, a ratio approaching two could be predicted for the evolution in the "Z" restitution quality (Rodriguez *et al.*, 1986).

SUMMARY OF THE SPOT STEREOSCOPIC IN-FLIGHT ASSESSMENT

This report covers a set of restituted points. A planimetric accuracy of 6 metres was obtained. Altimetric accuracies of 3.5 m for $B/H = 1$ and 7 m for $B/H = 0.5$ can be obtained. Six to eight Ground Control Points are sufficient to obtain accurate and reliable modeling of SPOT stereopairs. No significant difference was found between the use of panchromatic and multispectral images.

A certain number of problems were, however, brought to light:

Problems specific to the work undertaken:

- the ground points were selected beforehand, without the use of SPOT imagery
- the operators had not been trained on SPOT imagery
- The viewing quality was very irregular

General problems:

Geometric problems related to the choice of an analog channel:
- Film geometry (Vizir restitution, development, aging)
- Distortion of film on the stereoplotter

Interpretation problems:
- Use of negative film
- panoramic effect, once the two incidence angles become unsymetric with respect to the vertical
- Variation in the "x" plate scale
- Unsuitable optical enlargement
- Local contrast non-optimal and variable from one image to another
- Too much time between viewings

PROSPECTS FOR THE FUTURE

The present study gives a favorable indication regarding the future expansion of this type of application in the years to come.

With physical modeling of viewing geometry, the accuracy in *the formation of stereomodels* is guaranteed to within 10 metres in X, Y, and Z using only six to eight ground control points. These results owe much to the geometric simplicity of SPOT images.

In other respects, the French IGN is currently investigating the simultaneous modeling of a set of stereomodels utilizing a very reduced number of ground control points. The increase in productivity to be expected from this method, known *as spatial triangulation*, should rival that previously afforded by the use of aerial triangulation.

Table 3. Effect of the B/H Ratio on the Check Point Residuals Obtained

	filtering per modeling	overall filtering
Configuration $+27°/-27°$, $B/H=1$	X : 3.9 m, Z : 3.5 m Y : 4.4 m, P : 3.9 m	X : 3.8 m, Z : 3.4 m Y : 4.2 m, P : 3.9 m
Configuration $0°/\pm 27°$, $B/H=0.5$	X : 5.2 m, Z : 6.2 m Y : 4.5 m, P : 4.4 m	X : 4.6 m, Z : 6.7 m Y : 4.4 m, P : 4.4 m

TABLE 4. SUMMARY

			Raw Residuals		Filtering Per Modeling		Overall Filtering	
			No. of measurements	RMS	No. of measurements	RMS	No. of measurements	RMS
Modeling Residuals (Ground Control Points)		X	561	4.5 m				
		Y	561	4.1 m				
		Z	561	4.1 m				
		P	561	2.8 m				
Restitution (Check Points)	All stereopairs	X	631	8.0 m	559	4.8 m	557	4.6 m
		Y	631	6.6 m	587	4.5 m	589	4.4 m
		Z	631	7.1 m	584	5.3 m	593	5.3 m
		P	631	4.6 m	613	4.2 m	618	4.1 m
(excluding 4 points obviously false)	Northerly region, all stereopairs	X	245	9.8 m				
		Y		8.8 m				
		Z		8.8 m				
	Southerly region, all stereopairs	X	386	6.5 m				
		Y	386	4.7 m				
		Z	386	5.8 m				
		P						
	Configuration +27°/−27° All regions	X	215	8.1 m	179	3.9 m	180	3.8 m
		Y	215	5.5 m	205	4.4 m	205	4.2 m
		Z	215	4.3 m	206	3.5 m	209	3.4 m
		P	215	4.0 m	212	3.9 m	214	3.9 m
	Configuration 0°/±27° All regions	X	394	7.8 m	360	5.2 m	352	4.6 m
		Y	394	7.2 m	360	4.5 m	360	4.4 m
		Z	394	8.3 m	360	6.2 m	379	6.7 m
		P	394	4.9 m	360	4.4 m	384	4.4 m

The photogrammetric photographic channel will be implemented by using SPOT images on photographic film, on analytical stereoplotters with a control system adapted to the SPOT geometry. Certain of the defects mentioned in this report (identification of details, accuracy) will be corrected by using positive film with optimization of local contrast, anamorphic correction applied in the "line" direction to compensate the panoramic effect, and an increase in the number of fiducial marks to improve film distortion correction. These corrections were done for the first tests undertaken by IGN.

These first tests show that contour lines of 20 metres can be plotted for heavily featured landscapes, this figure being reduced to 10 metres over lightly featured land. These results are better than expected (Baudoin, 1983).

In addition, development of the *digital photogrammetric channel* will coincide with that of digital stereoplotters such as the TRASTER T5N from MATRA. The direct use of digital images will give increases both in productivity and accuracy.

Lastly, *the automatic generation, by correlation, of digital terrain models* with accuracies in the 10-metre class may also be considered, with a greater productivity than with conventional methods.

Such developments, taken with the parallel developments in cartographic data bases, lead definitely to a new era in cartography.

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Forthcoming Articles

Kenneson G. Dean and *Leslie A. Morrissey*, Detection and Identification of Arctic Landforms: An Assessment of Remotely Sensed Data.

Thomas Frank Eidel and *Janice L. Crouch*, The ARSUP Database and It's Access through the CMCIRS Catalog: Making Available to the Public Digital Maps from the ARSUP Process.

Michael Fleming, An Integrated Approach for Automated Cover-Type Mapping of Large Inaccessible Areas in Alaska.

Scott L. Huang and *Robert C. Speck*, Digital Image Processing for Rock Joining Surface Studies.

James A. Rogers and *Robert M. Bennett*, An AutoCAD-Based Mapping System for Encoded Stereoplotters.

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