EUGENE E. DERENYI
Department of Surveying Engineering
University of New Brunswick
Fredericton, N.B. E3B 5A3, Canada

Skylab in Retrospect

Ground coordinates of points imaged on photography taken from space can be determined consistently on the order of 0.020 mm at the scale of the imagery.

ABSTRACT: *Investigations conducted at the University of New Brunswick into the accuracy attainable for horizontal control extension using Skylab/EREP S-190A and S-190B imagery are reviewed. Single image and multiple image processing are discussed and it is shown that simple space resection procedures can give results compatible with more sophisticated aerial triangulation techniques. The* RMSE *values in* X *and* Y *coordinates ranged from 35 m to 75 m for S-190A photography and was on the order of 20 m photography for the S-190B imagery.*

The results obtained and the experience gained form a basis for predictions and recommendations pertinent to future space photography missions. In particular, the expected performance of the Large Format Camera, proposed for use in the Space Shuttle missions of the early 1980's, is discussed.

INTRODUCTION

ON 11 JULY 1979 the Skylab space station came crashing down to earth in a flaming shower of debris. Thus, a chapter in the history of space exploration had ended; an important one that can justly be regarded as a milestone in scientific achievement. Now that the controversy surrounding its re-entry has subsided, it is appropriate to review the invaluable experience gained by photogrammetrists from this space mission and to relate these experiences to future endeavors.

To date, the two cameras of the Skylab/Earth Resources Experimental Package (EREP) provided the closest approximation to metric photographs taken from space of the Earth's surface. The S-190A multispectral film camera and the S-190B Earth terrain camera provided imagery at such scales, resolution, and geometric quality as to allow meaningful study of the photogrammetric application of space photography. These images also have afforded an excellent opportunity for insight into the accuracies which will be obtainable from the next generation of orbiting sensors, such as the Large Format Camera (LFC), scheduled for use in the Space Shuttle flights of the early 1980's, and the modified Zeiss RMK 30/23 camera, designed for installation in Space Lab. With Skylab, the era of "Space Photogrammetry" has now dawned.

Surprisingly enough, very little has been published in the open literature on the photogrammetric evaluation of Skylab imagery. Perhaps the article by Keller (1976), which appeared in *Photogrammetric Engineering and Remote Sensing,* is the only one published in any scientific journal. A few papers presented at various conferences, such as those by Ali and Brandenberger (1978), Derenyi (1976), and Petrie (1978), and technical reports of closed circulation, such as those by Garcia (1979) and Stewart (1975), are the only other sources of information.

This paper intends to rectify such an unfortunate oversight and to summarize the research which has been undertaken with the Skylab imagery in the Department of Surveying Engineering, University of New Brunswick (U.N.B.). All of the investigations were concerned with the planimetric point accuracy obtainable from the imagery. However, the tests evaluated both the S-190A and S-190B photography in block, single model, and

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single image mode. The five strips of photographs investigated included black-and-white as well as color films from each camera. Approximately 800 tests points were measured for the evaluation. For these reasons, the research at U.N.B. provided a comprehensive, rounded view of the capabilities and limitations of planimetric control extension with space photography and allows for well-founded observations pertinent to future space photography missions.

Data Acquisition

Details pertaining to the photography selected for this investigation are given in Table 1.

Strips I and II covered southern New Brunswick, the Bay of Fundy, and south-western Nova Scotia, Canada. Strips III and IV covered south-eastern Michigan and south-western Ontario, Canada. Strip V extended along the north-shore of Lake Ontario.

The diapositives used were third generation copies, printed at the scale of the negatives. The approximate image scale of the S-190A photographs was 1:2,770,000 and that for the S-190B photographs was 1:950,000.

Approximately 800 test points were selected on the five strips. The majority of points chosen were road intersections situated outside of densely populated areas. Prominent points along coast-lines, shore-lines, and streams constituted the balance. On Strips I and II, large, forest-covered areas made point selection rather difficult. In addition, a bluish haze was evident on the color photographs of Strip II, which decreased the contrast. On the other hand, Strips III, IV, and V mainly covered rural and urban areas with a dense road pattern, and selection of well-defined points posed less of a problem.

Image coordinates were measured in a Zeiss PSK stereocomparator under 8× magnification. Strips I and V as well as one of the models in Strip III were measured in two independent sets. The standard error of one measurement, as computed from the double measurements, was 0.006 mm and 0.008 mm for the X and Y image coordinates, respectively, on the S-190A photography, and 0.004 mm for both the X and Y coordinates on the S-190B photography.

Correction of the observed coordinates for systematic errors proved to be problematic, because the calibration data provided could not directly be related to the imagery at hand, due to changes in the interior geometry of the cameras after the calibration had been performed.

Therefore, preprocessing of the measurements was restricted to (a) the reduction of comparator coordinates to a principal point, as defined by the central reseau mark in the S-190A camera or the intersection of the diagonals through the camera of the S-190B photographs, and (b) correction of the photo coordinates for the effects of Earth curvature (all ground coordinates were in the UTM projection system). The effect of atmospheric refraction is negligible at the 430 km altitude, for the purpose considered.

Ground control values for test points were obtained from 1:50,000, 1:25,000, or 1:24,000-scale topographic maps of the imaged areas. This proved a not entirely satisfactory procedure, because large-scale differences between the photographs and the maps caused considerable difficulty in identifying conjugate points. Furthermore, several map sheets were out of date and many features, which were well-defined on the photographs, did not appear on the maps. The map coordinates were measured on a coordinatograph.

Multiple Image Processing

Standard aerial triangulation procedures were followed in this phase of the investigation. First, independent models were formed with the analytical strip triangulation program NRC-34 of the National Research Council of Canada. All points measured in a particular stereo model were included in the relative orientation. Ten points were selected as pass points between each model. The root mean square error (RMSE) of the residual Y-parallaxes after relative orientation ranged from 0.005 mm to 0.012 mm. Adjustment to ground control was then performed with the Stuttgart Program PAT-M4, which is a planimetric block adjustment for independent models. A two-

Table 1. Test Material

Strip Code	Date	SL-3 Orbit	Camera	Film	Roll Number	Frame Numbers
I	1973-09-21	52	S-190A	Pan-X	47	312-316
II	1973-09-21	52	S-190A	Color	46	312-316
III	1973-08-05	14	S-190A	Pan-X	23	183-186
IV	1973-08-05	14	S-190B	Color	83	149-153
V	1973-09-09	29	S-190B	Pan-X	85	295-299

Note: f of S-190A = 152.451 mm; f of S-190B = 457.411 mm dimensional adjustment was considered to be satisfactory as it was not expected that any useful height information could be obtained because of the very poor base/height ratios.

With the exception of Strip III, a set of nine ground control points were used in the adjustments. These points were distributed in groups of three's located at the beginning, in the middle, and at the end of each strip. Strip III was adjusted to six ground control points only. Later, Strip I was re-adjusted to a set of 43 control points distributed over the entire length of the strip. However, no significant improvement was achieved in the results over those obtained with the nine point configuration.

At all points which were excluded from the adjustment, the discrepancies were formed between the map coordinates and the transformed image coordinates and then the RMSE of the discrepancies was computed. Points which showed a discrepancy larger than three times the RMSE were rejected and thus excluded from the computation of the final RMSE values. There were only 45 such points out of the approximately 800 which were measured. In Table 2 the RMSE of the X and Y coordinates and that of the horizontal position are listed for each strip.

All models in Strips I, IV, and V and two of the models in Strips II and III were also adjusted individually. Four ground control points were employed in each model. Table 3 shows the results obtained.

Single Image Processing

Strips I and V (both having five photographs) were included in this evaluation. Analytical space resection was performed for each photograph using six control points per image. Each test point with known ground coordinates was then "reprojected," using the collinearity equations, onto a plane surface having either the mean elevation of the control points used in the space resection or a zero elevation. The same procedure was repeated but with only the X and Y coordinates of the control points in the space resection. All reprojected point coordinates were then compared with map derived coordinates and the RMSE was calculated. The largest height differences on both strips were on the order of 250 m and, thus, the results obtained from the three methods of single image processing agreed with 0.001 mm at image scale. In Table 4 the RMSE values are listed for the simplest method, ie., space resection with X,Y coordinates only and reprojection onto a plane with a zero elevation.

Discussion of the Results

Table 2 indicates that the RMSE of the coordinates at check points range from 0.012 mm to 0.030 mm and the RMSE in position range from 0.018 mm to 0.038 mm at the scale of the image. Such results can be regarded as excellent, considering the fact that all control and check points were untargetted natural features and that many of the ground coordinates were obtained from 1:50,000-scale topographic maps. Map accuracy standards require that the position of well-defined features must be correct to 0.5 mm on the map, at the 90 percent confidence level. Thus, some control points could have been in error by up to 25 m, which corresponds to 0.009 mm and 0.026 mm at image scale on the S-190A and S-190B photographs, respectively. In fact, the higher accuracy obtained from Strip III versus Strip I (both S-190A photography) can be partly attributed to the availability of 1:25,000 and 1:24,000 scale maps of that area.

It is evident from Table 2 that the S-190B imagery gives the best result at ground scale. At image scale, however, the overall results obtained with the two types of photography are quite similar. Apparently, the high resolution and larger image scale provided by the S-190B camera has more than offset the somewhat lower precision of the internal geometry.

Color film (Strips II and IV) gave poorer results in both cameras than did black-and-white photography.

The RMSE values obtained at U.N.B. with the S-190B photography are somewhat larger than those achieved by Keller (1976). In his paper he

Table 2. RMSE of Discrepancies at Check Points after Block Adjustment

Strip Code	No. of Control Points	No. of Check Points	Root Mean Square Errors: Ground Scale in m: X	Y	Pos'n	Image Scale in mm: x	y	Pos'n
I	9	191	48	68	83	0.017	0.024	0.030
II	9	196	77	75	107	0.028	0.027	0.038
III	6	81	36	34	49	0.012	0.012	0.018
IV	9	130	19	28	34	0.020	0.030	0.036
V	9	136	18	18	26	0.018	0.019	0.027

TABLE 3. WEIGHTED AVERAGES OF RMSE VALUES OF DISCREPANCIES AT CHECK POINTS PER STRIP AFTER MODEL-BY-MODEL ADJUSTMENTS

Strip Code	No. of Models Averaged	Total Check in Strip	Root Mean Square Errors					
			Ground Scale in m			Image Scale in mm		
			X	Y	Pos'n	x	y	Pos'n
I	4	244	56	62	84	0.020	0.023	0.030
II	2	151	71	73	102	0.026	0.026	0.037
III	2	71	35	40	54	0.012	0.015	0.019
IV	4	168	25	21	32	0.026	0.022	0.034
V	4	149	17	17	24	0.018	0.018	0.025

Note: Four control points per model were used.

states that "the horizontal geodetic RMS error for the 15 withheld control stations was 15.068 metres." According to Keller's estimate, however, the accuracy of the control used in the block adjustment was significantly better than the accuracy of the control employed at U.N.B. Furthermore, Keller had only 15 check points available and most of them were located in the vicinity of stations used to control the block adjustment solution, whereas a total of 266 check points were distributed throughout the two S-190B strips investigated at U.N.B.

A comparison of Table 2 with Table 3 indicates that simultaneous adjustment of strips can yield positional accuracies compatible with those obtained by the adjustment of individual models. This was expected, as the strips were short and densely controlled. The results of the model-by-model adjustment reinforce, in every respect, the conclusions reached from the block adjustment.

Table 4 shows that the results from single image processing are very close indeed to those obtained from aerial triangulation adjustment. Again, the S-190B imagery provides the best accuracy at ground scale. The results at photo scale are very similar for all strips.

CONCLUSIONS AND RECOMMENDATIONS

It has been clearly demonstrated that ground coordinates of points imaged on photography from space can be determined consistently on the order of 0.020 mm at the scale of the image. This accuracy can be achieved by simple techniques such as planimetric block adjustment or space resection and reprojection onto a plane, a most significant finding for developing countries not having the computer resources to handle sophisticated aerial triangulation programs. Elevation data for control are not required to obtain good planimetric accuracy, although in areas of large relief variations their use is recommended.

It is obvious that the S-190B imagery has characteristics very similar to that of the Large Format Camera (LFC) to be orbitted in the Space Shuttle (Doyle, 1979). Resolution at ground scale is expected to be 14 m, which compares with the 15 to 30 m resolution of the S-190B imagery. The 1:1,000,000 scale of the proposed imagery almost matches the 1:950,000 scale of the S-190B photography.

Doyle quotes an expected ground positional accuracy of 15 m from LFC photography, which corresponds to 0.015 mm at the scale of that imagery. In view of the 0.016 mm positional accuracy attained by Keller (1976) and the 0.018 to 0.035 mm accuracy obtained in the extensive tests conducted at U.N.B., such expectation does seem reasonable, given the improvement in accuracy that will be realized by the fact that the LFC is designed as a metric camera.

TABLE 4. WEIGHTED AVERAGES OF RMSE VALUES OF DISCREPANCIES AT CHECK POINTS PER STRIP AFTER SINGLE IMAGE TRANSFORMATIONS

Strip Code	No. of Photos Averaged	Total Check in Strip	Root Mean Square Errors					
			Ground Scale in m			Image Scale in mm		
			X	Y	Pos'n	x	y	Pos'n
I	5	244	64	71	96	0.023	0.026	0.034
V	5	149	21	20	29	0.022	0.021	0.030

Note: Six control points per photo were used.

Further improvement in the accuracy can be facilitated by rectifying, in future space photography missions, the problems encountered with the Skylab imagery. The following recommendations are now made:

- Ground points to be used as control data in the photogrammetric evaluation of space photography should have their ground coordinates known to a few metres' accuracy. It is not a satisfactory procedure to obtain ground control values from topographic maps. Needless to say, this is a stringent requirement, because the real benefits of space photogrammetry will be realized in unmapped or poorly mapped regions where, by the same token, accurate ground control data are in short supply or else unavailable. However, a spacing of the control points about 100 km apart proved sufficient for the block adjustment of the S-190B strips and the LFC will allow a spacing extended to 500 km or further. Therefore, Doppler satellite triangulation and Global Satellite Positioning could be employed to acquire ground control data in such regions.
- All ground control points should be well-defined features. Intersections of linear features such as roads, railways, and transmission lines provide excellent targets for observation on the measuring instruments. In hinterland areas where there is an absence of manmade features, appropriate point marking should be devised, such as cut lines in the vegetation cover, or discoloring the soil by aerial spraying.
- A complete, up-to-date set of camera calibration data should be available for all space imagery used for photogrammetric work.

Finally, it is to be emphasized that the tests conducted with the Skylab S-190A and S-190B photographs have proved beyond any doubt that space photogrammetry is a feasible media for horizontal control extension.

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tational power of the host computer for on-line applications programs and concurrent general-purpose computations in a multi-tasking environment.

Another unique feature of the US-2 is the optional freehand *XY*-input control. This control acts like a digital input pantograph and provides the operator with an extremely effective and convenient method for controlling model motion and performing plotting operations. Another option available with the US-2 is a 6× to 27× continuous zoom system.

The current R&D activities at HAI include development of control systems and software for a new series of TA3/P1 stereocomparators. These systems involve simultaneous real-time control of these *XY*-stages and associated rotation and zoom optics. In addition, several other study efforts in the area of digital image processing are currently in process.

HAI has its offices and production facilities at 21421 Hilltop Street, Southfield, Michigan 48034; telephone (313) 352-2640.