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Height Measurements from Satellite Images*

Various base-height ratios and magnifications were tested with the Zoom Height Finder using Skylab and Landsat Imagery.

INTRODUCTION

THE INCREASED UTILIZATION of satellite imagery has raised numerous questions concerning its potential for measurement tasks. Previous discussions by Petrie (1970), Welch (1972) and others, for example, concluded that while planimetric mapping from small-scale satellite images was a definite possibility, the potential for obtaining reasonable height measurements was severely limited by altitude, geometry, and resolution. To date these predictions have proved correct, with Skylab and Landsat images being used to produce map products at scales as large as 1:250,000 meeting planimetric map accuracy standards (Colvocoresses and McEwen, 1973; McEwen and Schoonmaker, 1975; Trinder, 1976). Investigations of the possibilities for deriving height data, however, have been limited to a few experiments primarily oriented toward obtaining planimetric coordinates from Skylab images by aerotriangulation procedures (Mott, 1975a, 1975b; Stewart, 1975; Keller, 1976). In these experiments typical Z residuals after strip adjustments ranged from ±100 to greater than ±200 m. Mott, for example, reported an RMSE in Z of ±117 m for a strip of four Skylab S-190A models and concluded that the minimum contour interval which could be plotted from these photographs was approximately 250 m.

ABSTRACT: *An instrument, the Zoom Height Finder, has been developed to investigate the possibilities of economically deriving height information from satellite images. Measurements of several stereopairs of Skylab photographs produced on color, color-infrared, and panchromatic films, and of overlapping Landsat images recorded on successive orbits resulted in minimum height difference errors of ±50 to ±300 m and absolute elevation RMSE's of ±150 to greater than ±300 m. Base-height ratios varied from 0.10 to 0.26, and the precision of stereometer measurements ranged from approximately ±3 to ±8 μm depending on the viewing magnification employed and the resolution (R) of the images. From these measurements the optimum viewing magnification was determined to be equivalent to 0.7R + 7. Improved* b/h *ratios and lower altitudes are required to obtain significant improvements in heighting accuracies.*

While these experiments verify the unfavorable conclusions concerning height measurements from satellite imagery, they tend to ignore factors such as instrumental accuracies, image resolution, viewing magnification, and the viewer's perception of the terrain, including his ability to perceive and measure *height differences*. It would appear that these factors become increasingly important as geometric conditions are weakened and image scales reduced. Furthermore, most users of satellite imagery de-

*Presented at the 42nd Annual Meeting of the American Society of Photogrammetry, Washington, DC, February 1976.

sire stereo as an aid to terrain interpretation rather than for topographic mapping (McEwen, 1974).

In consideration of these many factors, this paper is concerned with: (1) the development of an instrument, the Zoom Height Finder, designed to permit the economical derivation of heights from small-scale images using instrumentation and techniques comparable to those employed with aerial photographs; and (2) the interrelationships between factors such as base-height (*b/h*) ratio, image quality, viewing magnification, and the precision and accuracy of height measurements obtained from Skylab and Landsat models.

The Zoom Height Finder

The Zoom Height Finder is comprised of two units, a modified Bausch and Lomb Zoom 70 Stereoscope capable of 7× to 60× magnifications and a precision stereometer (Figure 1). The stereoscope is mounted over a light table (or over a detachable stage constructed around the base of a standard Zoom 70) which serves to support the precision stereometer. Rules are attached to the light table (or stage) to provide parallel guidance in the y-direction for a glass plate on which the photographic transparencies are mounted. Scanning of the stereo-model in the y-direction is accomplished by manual translation of the glass plate between the rules. Scanning in the x-direction is undertaken by rotation of the individual lenses which are a part of standard stereo-attachment for the Zoom 70.

The precision stereometer (which is similar in design and function to a parallax bar) consists of a steel rod on which a clear glass scale with a small dot reticle on its underside is attached by means of an adjustable slide (Figure 2). A second, similar glass scale is fixed to a housing containing a mechanical drive mechanism, which in turn is connected to a precision micrometer head graduated to 0.001 mm. Turning the micrometer head drives the rod, and thus the scale attached to the rod, in the x-direction. Since elevation measurements are a function of the x-separation (or x-parallax) of corresponding points recorded on pairs of overlapping photographs as indicated by the floating dot principle, the extremely precise measurement of the x-separation of the dots on the glass scales is required. This may be accomplished by direct readings from the micrometer head, or from a dial gauge (0.002 mm graduations) mounted so as to measure the parallax independent of backlash in the micrometer drive mechanism.

In order to utilize the Zoom Height Finder, a stereo-pair of overlapping images are mounted on the glass plate so that their base lines are properly aligned. The glass plate is then inserted between the rules on the stage plate and translated in the y-direction to the image points of interest. The individual lenses of the Zoom 70 stereo-attachment are rotated to eliminate y-parallax and the magnification adjusted to provide optimum view-

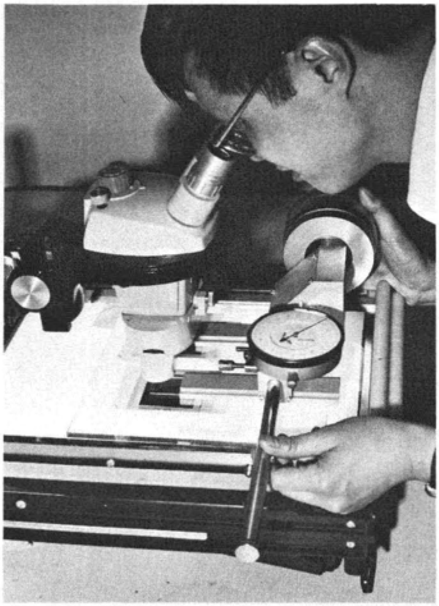

FIG. 1. The Zoom Height Finder is comprised of two units, a modified B & L Zoom 70 Stereoscope and a precision stereometer.

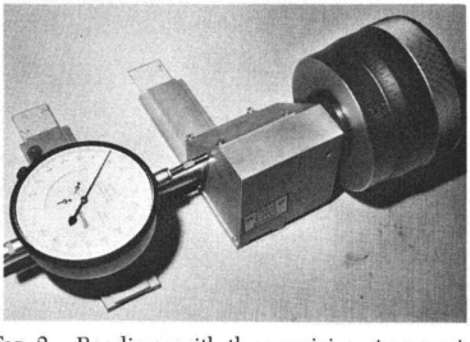

FIG. 2. Readings with the precision stereometer may be obtained from a micrometer head graduated in 0.001 mm units or from a dial gauge mounted so as to be independent of backlash in the micrometer head.

ing of the stereo-model. Next, the precision stereometer is placed on the stage plate and the x-separation of the dots approximately established by loosening the adjustment screw of the mount for the glass scale on the rod and sliding the scale in the x-direction. Any y-parallax may be eliminated by individual y-adjustment of the glass scales. The focusing of the stereo-model is then refined and the micrometer head turned until the individual marks on the right and left scales merge and appear to "float" on the surface of the terrain. The micrometer and/or dial gauge reading is recorded and the stereometer moved to the next point. With the Zoom Height Finder, x-parallax readings have been established to a precision of $\pm 2\mu$m.

Skylab and Landsat Model Characteristics

The important characteristics of the Skylab and Landsat images used to form the stereo-models for these tests are summarized in Table 1. The base-height ratios are particularly worthy of note. For example, the Skylab S-190A photographs were exposed with photo bases of approximately 20 mm and 40 mm which when related to the focal length of 152 mm for the Multispectral Photographic Facility (MPF) provide b/h ratios of about 0.13 and 0.26 respectively. The 0.26 b/h ratio does not differ significantly from the usual 0.3 b/h ratio for a standard 12-inch focal length photogrammetric camera and, because the MPF is a metric camera system with between-the-lens shutter mechanisms, heighting accuracies obtained with these S-190A photographs should be indicative of the potential of conventional photogrammetric camera systems of comparable geometric characteristics. Quality of the MPF photographs generally was excellent with image resolutions for low contrast objects ranging from 20 to 50 lpr/mm depending on the type of film employed (Welch, 1974).*

The S-190B Earth Terrain Camera (ETC) photographs used in this study were limited to a single model of the Salton Sea region recorded on Eastman Kodak SO-242 high-resolution color film. A 45mm photo-base produced a b/h of about 0.10, and the image resolution of approximately 35 lpr/mm for low-contrast objects provided a stereo-model of excellent definition (Welch, 1976).† The use of a focal plane shutter in the ETC system, however, is reported to cause a slight scale change in the flight direction and, consequently, x-parallaxes may be somewhat distorted (Mott, 1975a; Keller, 1976).

The Landsat images were recorded in a continuous strip with the multispectral scanner (MSS) and have been artificially segmented into 185 × 185 km scene formats by NASA (NASA, 1976). Stereoscopic models must be formed with images recorded on adjacent orbits and, due to the near-polar orbit, sidelap increases from approximately 14 percent at the equator to about 85 percent at 80° N or S latitude. Since it was desirable to conduct stereo-measurements at more than one b/h ratio, models were obtained for three areas on the mountainous west coast: San Francisco, California (b/h = 0.14), Vancouver, Washington (b/h = 0.12), and Juneau, Alaska (b/h = 0.10). The ground resolution of these Landsat images is about

*Equivalent to ground resolutions of 145 to 60 m.
†Equivalent to a ground resolution of 25 m.

Table 1. Skylab and Landsat Models.

System & Scale	Area	Satellite Altitude (H)	B/H Ratio	Spectral Band and Resolution (lpr/mm)
S-190A (1:2,850,000)	San Francisco, CA (38°N Lat.)	435 km	0.26, 0.13	Red (50), IR (20), Color (35), CIR (20)
	Salton Sea, CA (33°N Lat.)	435 km	0.13	Red (50), IR (20), Color (35), CIR (20)
S-190B (1:950,000)	Salton Sea, CA	435 km	0.10	Color (35)
Landsat-1 (1:3,369,000)	San Francisco, CA	919 km	0.14	Bands 5 and 7 (15)
	Vancouver, WA (46°N Lat.)	919 km	0.12	Bands 5 and 7 (15)
	Juneau, AK (59°N Lat.)	919 km	0.10	Bands 5 and 7 (15)

200-250 m for low contrast targets (Welch, 1974; Figure 3).

In contrast to the Skylab photographs, the Landsat MSS images are generated in successive cross-track strips (comprised of six scan lines), and a central perspective comparable to that of a metric camera system does not exist (Colvocoresses, 1974; Kratky, 1974). Although NASA applies various geometric corrections to the MSS bulk images by appropriate deflections of the beam of the electron beam recorder (EBR), random scanning mirror wobble, spacecraft sweep non-linearity, attitude variations, and ground processing effects all cause errors which influence image positions, x-parallaxes, and, thus, height measurements (Derouchie and Forrest, 1974). It has been shown that planimetric errors can be reduced to less than a pixel in bulk images by fitting polynomials, but similar attempts to model elevation errors do not appear to have been conducted (Wong, 1975; Bahr, 1976; Konecny, 1976).

Height Difference Measurements

The basic equation for height differences is

$$\Delta h = \frac{H \cdot \Delta p}{b + \Delta p} \qquad (1)$$

H =altitude
b =photo base
Δp =difference in x-parallax between the top and bottom of the imaged object
Δh =height difference

When conducting measurements on small-scale satellite images, the precision to which Δp can be determined greatly influences the reliability of the calculated height difference (Welch, 1970). For example, assuming independent observations at the top and bottom of an imaged object, the error in parallax difference measurement (Δp_σ) can be estimated by:

$$\Delta p_\sigma = \sqrt{\sigma^2_a + \sigma^2_b} \qquad (2)$$

σ_a, σ_b =standard deviations for setting the floating mark at the top and bottom of imaged points, respectively

Substituting Δp_σ for Δp in the height difference equation yields the height difference error (Δh_σ). Obviously Δp_σ and thus Δh_σ can be minimized by viewing the stereo-model under optimum magnification.

In order to assess the relationship between Δp_σ and optimum viewing magnification, a set of ten stereometer readings was recorded at each 5× magnification increment between 10× and 60× for each of numerous control points identified on both U.S. Geological Survey map sheets (at 1:24,000 and 1:62,500 scales) and the stereo-models. From the sets of readings, the average Δh_σ (for each magnification/film type) was computed in parts per thousand (‰) of the satellite altitude (H) and plotted as a function of viewing magnification for both the Skylab and Landsat models (Figures 4 and 5). By taking the viewing magnifications representative of minimum Δh_σ values for each type of imagery, a graph of the relationship between optimum viewing magnification and image resolution in lpr/mm was obtained (Figure 6). For the conditions of this test the nearly linear relationship between magnification and image resolution is defined by the equation:

$$\text{Opt. Mag} = 0.7R + 7 \qquad (3)$$

where R =low contrast image resolution in l pr/mm.

Although this equation will vary for individual observers, it clearly indicates that conventional stereo-photogrammetric instruments with viewing magnifications of 10× or less are not optimum for performing measurements on small-scale satellite images.

Assuming average Δp_σ values of ± 5, 8, and 9 μm for the various Skylab and Landsat models, the corresponding height difference errors in meters were computed from Equation 1 for different b/h ratios (Figure 7). These curves take into account the precision of measurement at the top and bottom of the imaged object according to Equation 2. However, they do not reflect the photogrammetrist's problem of identifying the top and bottom of the imaged object. That is, the precision may be excellent— but to the wrong point. Consequently, the values indicated in Figure 7 are not always obtained in practice. It is also interesting to note that Δh_σ's for the ETC model are much smaller than those for the MPF stereo-pairs, despite the inferior base/height ratio. In practice this may be attributed to the larger format and photo-base; and to the increased scale which facilitates the identification of terrain points.

Height Measurements

Absolute elevations are given by spot heights and contours. In normal photogram-

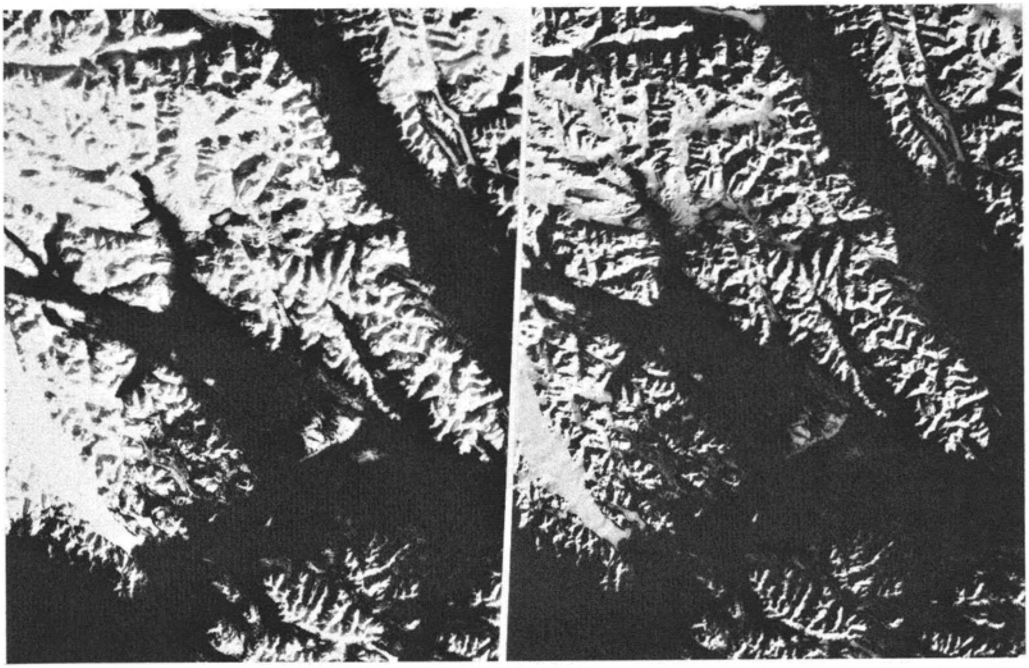

FIG. 3. Landsat stereo-pair of the Glacier Bay, Alaska region (Juneau model).

metric work involving aerial photographs and first- or second-order restitution instruments which correct for relief, tilt and earth curvature, spot heights are established to within about 0.15 to 0.30‰ H and contour intervals meeting U.S. National Map Accuracy Standards must be correct to 0.50 to 0.99‰ H. If these accuracy figures for aerial photographs are extrapolated to Skylab (H = 435 km) and Landsat (H = 919 km), the spot heights and contouring accuracies listed in Table 2 are obtained. Whereas these accuracies are admittedly gross in terms of most mapping requirements, they do illustrate the problem of obtaining reasonable elevation information from satellite imagery.

The Zoom Height Finder, in contrast to typical stereo-photogrammetric instruments, has a readout to 1 μm and permits the operator to view the stereo-model under optimum magnification (as compared to the usual fixed 6 to 10× viewing magnification of most mechanical projection instruments). However, the ZHF does not correct for dis-

FIG. 4. Height difference errors (Δh_σ) in parts per thousand of the altitude as a function of viewing magnification for some of the Skylab S-190A (20 and 40mm base) and S-190B (45mm base) models.

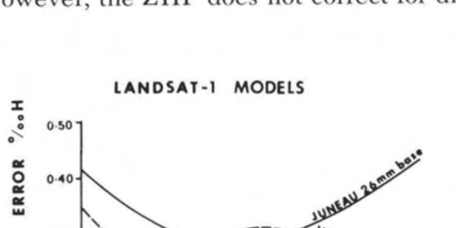

FIG. 5. Height difference errors (Δh_σ) in parts per thousand of the altitude as a function of viewing magnification for the Landsat models.

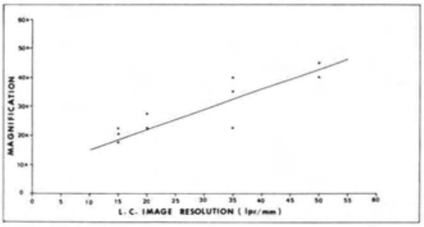

FIG. 6. Viewing magnifications resulting in minimum Δh_σ values plotted with respect to low contrast target image resolutions (R) of 15 (Landsat), 20 (S-190 IR/CIR), 35 (S-190 color), and 50 (S-190 panchromatic) lpr/mm. Optimum magnification = 0.7 R + 7.

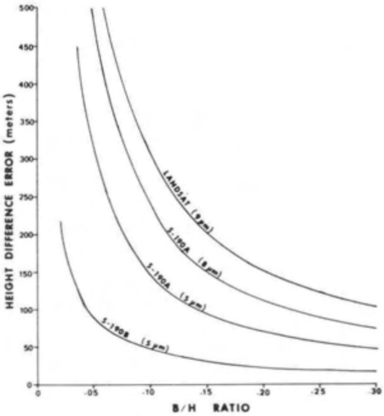

FIG. 7. Height difference errors (Δh_σ) calculated in meters as a function of base-height ratio for Δp_σ values of ± 5, 8, and 9 μm.

placements due to relief, tilt or earth curvature and this must be accomplished by means of a separate adjustment procedure. The method adopted for removing the effects of displacements is essentially that developed by Thompson (1954) and refined by Methley (1970) to obtain spot heights equivalent to 0.25 to 0.40‰ H from readings taken with a parallax bar and mirror stereoscope. In this method the adjustment is based on stereometer readings at a minimum of five control points (Figure 8). One point (A), near the midpoint of the baseline, serves as a reference point from which all elevation differences are computed by using Equation 1. With five control points it is then possible to solve for the unknown coefficients in the correction polynomial:

$$h' - h = a_0 + a_1x + a_2y + a_3xy + a_4x^2 \qquad (4)$$

where

- h' is the known height of the control point, or the true height of any model point.
- h is the crude height computed from Equation 1 with respect to A.
- x,y are model coordinates (in mm) with the origin at the center of the baseline.

Once the coefficients are known, the true height of any model point can be computed.

Because of the vast area covered by the small-scale satellite images and the availability of 1:24,000 and 1:62,500 topographic maps for the area of study, numerous control points could be identified. Taking advantage of these control points and Methley's suggested addition of a y^2 term, Equation 4 becomes:

$$h' - h = a_0 + a_1x + a_2y + a_3xy + a_4x^2 + a_5y^2 \qquad (5)$$

A sixth control point is required for Equation 5; however, this is easily obtained from the existing maps.

The polynomials of Equations 4 and 5 are similar to those employed by Wong (1975) and Bahr (1976) to refine planimetric image coordinates, and are intended to correct for displacements due to tilt and earth curvature. If desired, the measured x,y image coordinates can be reduced to "flat ground" by performing an initial height adjustment and employing these heights to re-

TABLE 2. CONVENTIONAL SPOT HEIGHT (S. H.) AND CONTOUR ACCURACIES EXTRAPOLATED TO SKYLAB AND LANDSAT ALTITUDES

	S.H. (0.15 − 0.30‰H)	C.I. (0.50 − 0.99‰H)
Skylab	65 − 130 m	220 − 435 m
Landsat	140 − 275 m	460 − 910 m

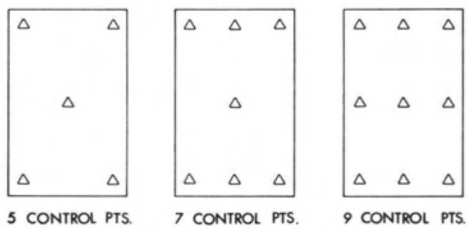

FIG. 8. Ideal distributions for five, seven and nine control points.

fine the planimetric coordinates. A second height adjustment is then undertaken with the refined coordinates. While this latter procedure has proved satisfactory with aerial photographs, it is not required with satellite images on which relief displacements are very small.

The reduction of a stereometer measurements according to the above principles is easily undertaken with programmable electronic desk calculators (such as the Wang 500), and if more than the minimum number of control points are available a least-squares procedure may be adopted. For the measurements of the satellite image models in this experiment, observations performed at magnifications ranging from 10× to 30× were adjusted by using (1) Equation 4 with five control points; and (2) Equation 5 with a least-squares fit to seven and nine control points. Computed heights were then compared to the true heights of nine to 25 independent check points distributed throughout the models. The RMSE's (for the check points) varied according to model, magnification, and spectral band, and the results from the Skylab and Landsat models are considered in the following sections (Tables 3 and 4).

SKYLAB S-190A MODELS

The Skylab S-190A photographs of San Francisco provided a partial model with a *b/h* ratio of 0.26. Five control points were used with Equation 4 for the adjustment and an average RMSE of ±148 m was obtained for the color, color infrared, and black-and-white (red band) stereopairs. This "good" result is equivalent to 0.34‰ *H*, and may be attributed to the favorable *b/h* ratio and limited model section to which the polynomials were fitted. It is interesting that neither viewing magnification nor image resolution appear to have significantly influenced the results.

A color stereopair of the Salton Sea with a *b/h* ratio of 0.13 was also measured and adjustments conducted with five, seven and nine control points. In this instance, control points and check points distributed throughout the entire model were utilized and marginal improvements in the RMSEs correlated with 20× to 30× viewing magnifications and adjustments based on nine control points.

A color model of the Salton Sea recorded by the S-190B ETC camera yielded RMSE's of 500 to 675m with the best results obtained with the measurements conducted at 30× viewing magnification. The weak *b/h* ratio of 0.10 and the effects of the focal plane shutter contribute to the large residuals.

LANDSAT MODELS

The RMSE's for the Landsat models reveal that the smallest residuals were obtained for the measurements conducted on band 5 images with 20× to 30× viewing magnifications and which were adjusted to 9 control points (Table 4, Figure 9). As is to be expected, residuals tend to increase as the *b/h* ratio is decreased from 0.14 to 0.10.

In general, it appears that spot height accuracies with the Landsat images used in this experiment are limited to approximately ±300m (0.33‰ *H*) and that, due to the errors introduced by the scanning system, optimum results are obtained by partitioning the model (similar to the San Francisco model) and by utilizing a least-squares adjustment based on nine or more control

TABLE 3. S-190A ABSOLUTE HEIGHT MEASUREMENT RMSEs

Model	No. of Control Points	RMSE(m) at Viewing Magnifications 10×	20×	30×	Mean RMSE(m)
San Francisco *b/h* = 0.26 (Partial model)					
Color	5	177	197	197	
Color Infrared	5	114	211	120	148
Red (B/W)	5	133	139	139	
Salton Sea *b/h* = 0.13					
Color	5	548	384	314	
	7	415	408	456	398
	9	351	368	338	

Table 4. Landsat Absolute Height Measurement RMSEs

Model	No. of Control Points	RMSE(m) at Viewing Magnification 10×	20×	30×	Mean RMSE(m)
San Francisco, CA					
$b/h = 0.14$					
(Partial model)					
Band 5	5	909	808	363	
	7	692	550	366	536
	9	443	369	328	
Band 7	5	448	488	390	
	7	419	399	414	413
	9	389	402	373	
Vancouver, WA					
$b/h = 0.12$					
Band 5	5	649	310	382	
	7	685	393	441	438
	9	454	313	318	
Band 7	5	712	746	629	
	7	985	853	960	740
	9	630	537	606	
Juneau, AK					
$b/h = 0.10$					
Band 5	5	836	410	820	
	7	792	389	519	598
	9	720	411	489	
Band 7	5	4972	1331	821	
	7	1444	1040	750	1520
	9	1302	1194	824	

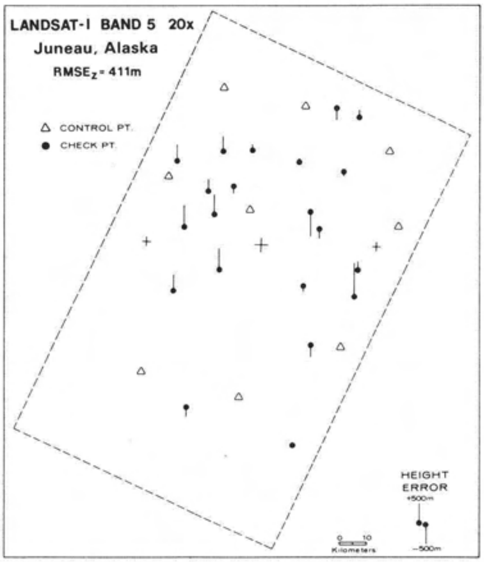

Fig. 9. Height residuals for the Juneau model after adjustment to nine control points. Observations recorded at 20× magnification.

points. In any event, height measurements from Landsat type images will be of minimal value unless b/h ratios are significantly improved and altitude reduced.

Conclusion

Results obtained with a precision instrument, the Zoom Height Finder, developed to assess the possibilities of economically deriving elevations from stereopairs of Skylab and Landsat images confirm the anticipated difficulties of obtaining height information from satellite data. Parallax difference measurement errors of ± 5 to $\pm 9\ \mu$m, for example, obtained with the Skylab and Landsat stereopairs viewed under optimum magnification were equivalent to ΔZ ground values of 50 to 320m. Absolute elevations, on the other hand, obtained with the aid of polynomials fitted by the method of least-squares to measurements of ground control points yielded RMSE's of approximately ± 150 m and ± 400 m for the Skylab and Landsat models with the most favorable b/h ratios. In general, minimum elevation errors were obtained by partitioning the models, using 20× to 30× viewing magnifications, and adjusting to nine control points. While it is possible that errors could be further reduced by employing higher order polynomials in the adjustment procedure, significant improvements in elevation determination will only occur as a result of larger b/h ratios and lower altitudes.

The results of this experiment also clearly indicate that small-scale satellite images must be viewed and measured under considerably higher magnifications than are available with most commercial photogrammetric instrumentation. For the conditions of these tests, the viewing magnification which resulted in the minimum errors was related to image resolution (R) by the linear equation

$$\text{Opt. Mag.} = 0.7R + 7 \ .$$

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408 Remote Sensing Theory and Techniques	4 sem. hrs. (RS)
409 Optics and Industrial Surveying	3 sem. hrs. (OP)
505 Photogrammetry I	5 sem. hrs. (PG)
508 Remote Sensing Applications	4 sem. hrs. (RS)
605 Photogrammetry II	4 sem. hrs. (PG)
805 Analytical Photogrammetry	5 sem. hrs. (PG)

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