A High Precision Photogrammetry Geodetic Positioning Cost Model

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ABSTRACT: The basic structure of a precise photogrammetric geodetic positioning cost model is developed and described. Input and intermediate variables are defined. The model consists of the three basic component costs: labor, transportation, and equipment. Planning, monumentation, targeting, photography, and data handling subcomponent costs may contribute to each component cost. A procedure for analyzing probable input uncertainties is presented, and the cost errors are analyzed. The model is calibrated with two large-scale precise photogrammetric positioning projects for which reliable cost data exist. The high precision photogrammetry positioning cost model might be considered as a prototype for other photogrammetric cost prediction activities.

INTRODUCTION

ANALYTICAL PHOTOGRAMMETRIC METHODS of horizontal geodetic control extension have proven very cost effective for area-wide control densification applications. Better than 5-centimetre horizontal precisions have been reported for points located photogrammetrically by use of a specially designed reseau cone with the aerial camera (Slama, 1978; Lucas, 1981). This cone projects on the photograph a uniform set of reseau images which, when measured in resulting photographs, help significantly reduce systematic errors.

THE BASIC EQUATION

The National Ocean Survey (NOS) project in Ada County, Idaho, was the primary guide used to develop this cost model. Additional references added credence to system design. As reported by Grün (1982), the horizontal accuracy potential of modern self-calibrating bundle block adjustments was about 2.5 micrometres at the scale of the photograph. The Ada County project attained a horizontal point precision reliability between adjacent section corners (5,280 feet) of about 4.5 centimetres, or about 2 micrometres at the scale of the photograph. The accuracy predicted by Grün would have been 6 centimetres. Perry (1981) stated the following: "The expected RMS error in metres is equal to 1:500,000 of the inverse of the scale." Photo scale is expressed as shown in Equation 1, where photo scale (S) is equal to the camera focal length (f) divided by the flying height (H) above the ground; i.e.,

$$S = f/H. \qquad (1)$$

The expected error (EE),* in metres, may be related to the photo scale as indicated by Equation 2; i.e.,

$$\mathrm{EE} = (1/500,000)(1/S). \qquad (2)$$

The expected error is a product of the allowable error ratio (AE) and the separation distance (SD) between points being positioned. The typical wide-angle aerial camera focal length is about 0.150 metres. Making substitutions and solving for H in Equation 1 produces

$$H = 75,000(\mathrm{SD})(\mathrm{AE}). \qquad (3)$$

The ground dimension (G) of a single 9-inch by 9-inch wide-angle photograph is expressed as 1.5 times the value of H. Typical photographic coverage is characterized by a block of photographs having 67 percent endlap and 67 percent sidelap in the primary coverage. A block of photographs with 67 percent endlap and 33 percent sidelap comprises the secondary coverage, obtained from flight lines that are perpendicular to primary coverage flight lines. Photogrammetric design requirements specify that each targeted point on the ground be imaged on a minimum of nine primary coverage photographs. These details are used to compute the number of photographs required for primary coverage (NPPC) as shown in Equation 4; i.e.,

$$\mathrm{NPPC} = (((3(A)^{\frac{1}{2}})/G) + 1)^2 \qquad (4)$$

where A is the ground area involved in square metres.

* A list of acronyms and their definitions is included in the Appendix.

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This is the basic equation, linking required accuracy, flying height, and project area in a computation that determines the number of photographs necessary to achieve complete primary coverage.

COST MODEL STRUCTURE

The first step in determining cost involves a determination of the major components of a high precision photogrammetry project. Photogrammetric geodetic positioning is a more precise extension of analytical photogrammetry, and most of the project tasks are similar. Lafferty (1972) divided analytical photogrammetry projects into four classes: corner search and premarking, field survey control, photogrammetric costs, and calculations and final monumentation. Carpenter (1978) listed the five steps of any photogrammetric project as research and planning, reconnaissance, premarking, control survey, and tie-in and layout. These earlier ideas were combined with the Ada County test breakdown of tasks to develop the components of this cost model.

Three basic project cost components selected for use in this cost model were equipment and materials, labor, and transportation. The various project tasks of planning, monumentation, targeting, photography, photo measurement, and data reduction and adjustments were organized as parts of the basic costs.

The amount of existing control plays an integral role in dictating the applicability of this cost model to any particular area-wide positioning task. A detailed analysis of the original existing Ada County network revealed that additional ground survey densification would be required in order to improve the scale of the network (Gergen, 1981). Application of this cost model should be considered possible only when a minimum of one quality horizontal control point is available for every multiple of five primary coverage airbase dimensions around the perimeter of the project area.

PHOTOGRAPHIC COSTS

Half as many secondary coverage photos as primary photos are required due to their differing amounts of overlap. A separate color coverage, flown at about one-third of the primary coverage flying height to aid in target identification, is considered essential. The number of photos in this coverage will be about 1.24 times the number of primary photos when there is approximately 11 percent sidelap and 11 percent overlap. Total photographic cost (TPHC) is computed with Equation 5; i.e.,

$$\text{TPHC} = 1.24\,(\text{NPPC})\,(\text{NPM})\,(\text{CCP}) + 1.5\,(\text{NPPC})\,(\text{CBWN}) \qquad (5)$$

where

NPM = number of target identification print copies,
CCP = cost of one color print, and
CBWN = cost of one black-and-white negative.

The flight transportation cost (CFT) is derived from many factors. The total flight distance is a function of the number and length of all flight lines, turnaround distance between flight lines, and the distance between the airfield and the project area (DAC). CFT is computed using Equation 6; i.e.,

$$\text{CFT} = (\text{CAH}/\text{RA}(1{,}000))\,(8.03(A)/G + 18.8(A)^{\frac{1}{2}} + 478{,}300(\text{AE})(\text{SD}) + 2(\text{DAC})) \qquad (6)$$

where CAH is the aircraft cost per hour and RA is the aircraft's airspeed in kilometres per hour.

TARGETING COSTS

Targeting costs are computed in the three categories of transportation, labor, and equipment. Almost 20 different initial inputs are directly involved.

The fuel cost per gallon (FCPG), ground vehicle miles per gallon (TMPG), and cost per kilometre (CPKM) are used to generate the overall ground transportation cost per kilometre (TCHP) in Equation 7; i.e.,

$$\text{TCHP} = ((0.621(\text{FCPG})/\text{TMPG}) + \text{CPKM}). \qquad (7)$$

The total number of stations to be positioned (NS) is the combination of all existing (NSI) and new (NSJ) points. The ratio of painted targets per 100 ground points (PPS) and the ratio of paneled targets per 100 ground points (PDS) are based on Equations 8 and 9, respectively; i.e.,

$$\text{PPS} = \text{PPT}\,(\text{PDT} + 1) \qquad (8)$$

$$\text{PDS} = \text{PDT}\,(1 - \text{PPT}) - \text{PPT} + 1 \qquad (9)$$

where PPT is the ratio of stations per 100 ground points requiring painted targets and PDT is the ratio of stations per 100 requiring double targets.

The number of crew days (actually shifts) required to locate and set all panels and targets (TCD) is also based on the average time needed to locate each ground station (TLM), and the average times required to set a painted (TSPT) and a paneled target (TSLT). The average ground vehicle rate of travel (R) and the average distance from the office to the project area (DGT) are also used in Equation 10. The constants are used for unit conversions. Thus,

$$\text{TCD} = (\text{DGT}/4(R)) + (\text{NS}/8)((\text{TLM}(S)/1{,}000(\text{SD})) + \text{TSPT}(\text{PPS}) + \text{TSLT}\,(\text{PDS})). \qquad (10)$$

The total ground vehicle distance required for targeting (TTD) is computed by Equation 11, adding all in and out trips to the combined distance needed to visit each station once. The units of TTD are kilometres. Thus,

$$\text{TTD} = 2(\text{DGT})(\text{TCD}) + \text{NS}(\text{SD})/1{,}000. \qquad (11)$$

The total targeting time in days (TD) is found by use of Equation 12; i.e.,

$$\text{TD} = \text{TCD}(1 + (0.25(\text{DGT})/R)) \qquad (12)$$

The number of target maintenance crews (NCREW) is computed assuming that each target must be visited daily until the overflight is successful. This should significantly reduce target losses due to effects of nature and vandalism. Thus,

$$\text{NCREW} = (\text{NS}/8)(\text{PPLD}(\text{TSLT})(\text{PDS}) + 0.001(\text{SD})/R) \qquad (13)$$

where PPLD is the percentage of panels lost each day while waiting for the overflight.

Total ground distance traveled during target maintenance (TTCD), as a function of NS, SD, NCREW, DGT and the projected number of days until the overflight (DUF), is given by

$$\text{TTCD} = \text{DUF}(0.001(\text{NS})(\text{SD}) + 2(\text{NCREW})(\text{DGT})). \qquad (14)$$

The time in days required to pick up all panels (TPUD) is based on the cumulative distance between all ground stations, the number of panels, the time required to pick up a panel (PUPT) in hours, and the in and out travel time; i.e.,

$$\text{TPUD} = 0.25(\text{DGT})/R + 0.125(\text{NS})(0.001(\text{SD}/R + \text{PUPT}(\text{PDS})). \qquad (15)$$

Total targeting transportation cost (TPTTC) is based on the number of kilometres traveled and number of days of vehicle rental needed. Ground vehicle cost per day (TRPD) is used in addition to the vehicle cost per kilometre (TCHP), which results in

$$\text{TPTTC} = \text{TRPD}(\text{TD} + \text{NCREW}(\text{DUF}) + \text{TPUD}) + \text{TCHP}(\text{TTD} + \text{TTCD} + 2(\text{DGT}) + 0.001(\text{NS})(\text{SD})). \qquad (16)$$

Total targeting equipment cost (TPTEC) requires input of the costs of painted (CPT) and paneled (CLT) targets. Equation 17 takes into account the possible requirement to replace lost targets while waiting for the overflight; i.e.,

$$\text{TPTEC} = (1 + \text{DUF}(\text{PPLD}))(\text{NS}(\text{CLT})(\text{PDS})) + \text{CPT}(\text{NS})(\text{PPS}). \qquad (17)$$

Total targeting labor cost (TPTLC) is computed by multiplying the total number of crew days (shifts) by the daily cost of a targeting crew (DCTC) in dollars; i.e.,

$$\text{TPTLC} = \text{DCTC}(\text{TD} + \text{NCREW}(\text{DUF}) + \text{TPUD}) \qquad (18)$$

Planning Costs

Careful consideration of the NOS results for Ada County helped to generate the formula for planning labor costs (PPLC), shown as follows:

$$\text{PPLC} = \text{PR}(\text{TD} + \text{NCREW}(\text{DUF}) + \text{TPUD}) \qquad (19)$$

where PR is the planning cost per day in dollars.

Monumentation Costs

Many applications do not require the establishment of separate or new monuments. When a user of this cost model uses a value of zero for the variable TSM (time to set one complete station monument and its accessories), then the model assumes that no monumentation is required. When it is required, however, monumentation costs depend heavily on the computed value of the number of 8-hour monumentation days (MD) required to finish the task. N is the number of stations that can be monumented in one 8-hour period. This is used in Equation 20 to compute the amount of monumentation activity accomplished per 8-hour day; i.e.,

$$\text{TSM} + 2(\text{DGT})/R + (N - 1)(\text{TSM} + 0.001(\text{SD}/R)) = 8. \qquad (20)$$

The terms on the left side of Equation 20 were derived from a tabulation of monumentation rates listed in Table 1. This table illustrates the amount of distance traveled in kilometres and the time used in hours (in terms of basic variables DGT, R, TSM, SD, and N) for 1, 2, 3 and N stations being monumented per day.

Equation 21 expresses the fact that N is equal to the number of monuments to be set divided by the number of monumentation days used (MD); i.e.,

$$N = \text{NSJ}/\text{MD}. \qquad (21)$$

Substituting for N in Equation 20 and doing some rearranging results in

$$\frac{\text{NSJ}}{\text{MD}} = \frac{8 - \text{TSM} - 2\text{DGT}/R}{\text{TSM} + \text{SD}/1{,}000(R)} + 1. \qquad (22)$$

This is then simplified and solved for MD to yield

$$\text{MD} = \frac{\text{NSJ}(\text{TSM} + \text{SD}/1{,}000(R))}{8 - 2\text{DGT}/R + \text{SD}/1{,}000(R)}. \qquad (23)$$

Once MD is known, it is used to evaluate the total monumentation distance traveled in kilometres (TMDT):

$$\text{TMDT} = 2(\text{MD})(\text{DGT}) + 0.001\,(\text{SD})((\text{NSJ}/\text{MD}) - 1) \qquad (24)$$

The monumentation labor cost (PMLC), equipment cost (PMEC), and transportation cost (PMTC) are computed with Equations 25, 26, and 27, respectively. CCD is the daily crew cost, SMEC is the daily monumentation equipment cost, and CMM is the cost of materials to produce one monument and all its accessories. Thus

$$\text{PMLC} = \text{CCD}\,(\text{MD}), \qquad (25)$$

$$\text{PMEC} = \text{SMEC}\,(\text{MD}) + \text{CMM}\,(\text{NSJ}), \text{ and} \qquad (26)$$

$$\text{PMTC} = \text{TRPD}\,(\text{MD}) + \text{TMDT}\,(\text{TCHP}). \qquad (27)$$

Data Reduction and Adjustment Costs

These costs are computed in a manner that closely parallels the NOS methodology. The rate of plotting

TABLE 1. MONUMENTATION RATES

Stations Monumented per Day	Distance Traveled in Kilometres	Time Used in Hours
1	2(DGT)	2(DGT)/R + TSM
2	2(DGT) + SD/1,000	2(DGT)/R + 2(TSM) + SD/1,000(R)
3	2(DGT) + SD/1,000	2(DGT)/R + 3(TSM) + SD/1,000(R)
N	2(DGT) + (N − 1)SD/1,000	2(DGT)/R + N(TSM) + (N − 1)SD/1,000(R)

points per hour on maps (RPP), which was done in the field, the rate of image pointing (ROP) in number per day, and the cost of an office person (CPOP) per day are used here. The fact that six reseau images around each target image must also be measured is built into this computation. PFAF, the photogrammetric final adjustment factor, is input as the ratio of final total data manipulation and adjustment time to the total photogrammetric measurement time. This ratio was obtained from Perry's paper as 1.19 for the Ada County project. The measurement, reduction, and adjustment labor cost (PMRAC) is computed with Equation 28; i.e.,

$$\text{PMRAC} = \text{CPOP}\,(\text{PFAF} + 1)(30\,(\text{NPPC}/\text{ROP}) + ((1.5(\text{NPPC}) + \text{NS}\,(1 + \text{PDT}))/(8(\text{RPP}))) + (52.5\,(\text{NPPC})(G)^2\,(\text{NS}(1 + \text{PDT})))/(A(\text{ROP}))) \quad (28)$$

TOTAL COSTS

The total cost (TPCOST) is found by adding the total transportation cost (TPTC), the total labor cost (TPLC), and the total equipment cost (TPEC). All costs are in dollars. Subcomponents of the transportation costs include flight transportation cost (CFT), monumentation transportation cost (PMTC), and total targeting transportation cost (TPTTC). The labor cost is composed of the measurement, reduction, and adjustment labor cost (PMRAC); the planning labor cost (PPLC); the monumentation labor cost (PMLC); and the total targeting labor cost (TPTLC). Equipment costs include the cost of all prints and negatives (TPHC), monumentation equipment costs (PMEC), and targeting equipment costs (TPTEC).

MODEL LIMITATIONS AND ASSUMPTIONS

One accurate existing control point must be available around the project perimeter for every multiple of five primary flightline airbases. Primary coverage photos overlap 67 percent in both directions; secondary photos overlap 67 percent along each strip but have only 33 percent sidelap. A standard 150 mm focal length 9-inch by 9-inch format aerial mapping camera is assumed with a projected square reseau grid. This cost model was designed under the assumption that the project area has a nearly rectangular shape. Aircraft cost estimates may require reevaluation if the flying height required is greater than about 10,000 metres because of the special requirements for high altitude work. Painted targets might be considered maintenance-free, but all targets must still be visited daily to verify their presence. Because targets are uniformly spaced in the project area, the total transportation distance to visit each new point must be traveled during set out, maintenance, and pickup. Planning costs have been arbitrarily made a function of the number of crew days required to do these targeting tasks. This assumption is fairly safe because planning costs for the Ada County project were only about 3 percent of the total cost. Typically, six reseau images around each target image are pointed to and measured for each target image on all photographs.

The measurement, data reduction, and adjustment cost (PMRAC) is reliable only when at least three primary coverage flight lines exist. Otherwise, assumptions about the number of targets appearing on nine photos of primary coverage and the assumptions about pointings per target break down.

All hardware and software necessary to measure, reduce, and adjust the data are assumed to be available. These costs should be included with the appropriate labor charges.

Discount rates and inflation are not accounted for in this cost model. Input cost data must be an average projection over the entire project duration or all cost evaluations are based on costs for a given year. Per diem labor costs must be added to daily crew costs, if needed.

Input variable errors are assumed to have a normal distribution. Good input data are essential. Each computed cost depends entirely on the quality and reliability of the input data. Any one of the 37 different input values could cause a significant error if estimated or entered incorrectly. Applicability of this model to specific situations is dependent upon the knowledge and experience of the user.

ERROR DETERMINATION

The overall uncertainty associated with the total cost for a high precision photogrammetry positioning project is computed using the idea of numerically derived derivatives. The method is used to provide an estimate of the overall uncertainty associated with each computed cost.

The method is based on the definition for calculating the derivative of a function. This definition, written below as Equation 29, states that the derivative of a function (f) with respect to its variable (x) is equal to a limit (Thomas, 1966). This limit, computed as a small change in the variable x approaches zero, is evaluated by subtracting the normal value of the function from the value of the function when x is augmented by a small amount, and dividing by this same amount; i.e.,

$$f'(x) = \lim \Delta x \rightarrow 0((f(x + \Delta x) - f(x))/\Delta x) \qquad (29)$$

Example Error Computation

A simplified example of how Equation 29 was used is shown. A simple function (f) was computed by use of Equation 30; i.e.,

$$f = 3x^2 + 2y + z. \qquad (30)$$

The input values and their uncertainties (normal distribution one sigma assumed) were listed as

$$x = 10 \pm 2,\ y = 20 \pm 5, \text{ and } z = 50 \pm 1.$$

The value of the function was easily computed to be 390.

A comparison was conducted to verify the reliability of Equation 29. First, the actual partial derivatives were found and used to compute the true uncertainty of the function (σ_f) (Wolf, 1980).

$$\partial f/\partial x = 60,\ \partial f/\partial y = 2, \text{ and } \partial f/\partial z = 1.$$

$$\sigma_f = (((\partial f/\partial x)\sigma x)^2 + ((\partial f/\partial y)\sigma y)^2 + ((\partial f/\partial z)\sigma z)^2)^{\frac{1}{2}}. \qquad (31)$$

Because the partial derivatives $\partial f/\partial x = 60$, $\partial f/\partial y = 2$, and $\partial f/\partial z = 1$, the proper substitutions yield the following:

$$\sigma_f = ((60(2))^2 + (2(5))^2 + (1(1))^2)^{\frac{1}{2}} = 120.42. \qquad (32)$$

The value and uncertainty of the function f is 390 ± 120.42. Equation 29 was then used to evaluate the partial derivatives. Table 2 lists the partial derivatives for three possible values of delta. 1/10th, 1/1,000th, and 1/100,000th of the amount of each variable were used.

The uncertainty was computed for each delta value using Equation 31. 126.40 was computed for a 0.1 delta. 120.48 was computed for a 0.001 delta, and an uncertainty of 120.42 was computed for a delta of 0.00001. The computed derivative worked well and was accurate to five significant figures when a delta value of 0.00001 was used.

The Errors Program

The principle illustrated in the preceding example was applied to the computation of cost uncertainties. A simple computer routine was developed. Each of the 37 input variables was sequentially manipulated to find its partial derivative with respect to the total cost function through the use of Equation 29. The routine repeats a basic five-step process with each variable.

Table 2. Example Computed Partial Derivative Values

Variable Partial	Delta Values		
	0.1	0.001	0.00001
$\partial f/\partial x$	63.0	60.03	60.0003
$\partial f/\partial y$	2.0	2.0	2.0
$\partial f/\partial z$	1.0	1.0	1.0

The first step is to augment the variable in question by 0.00001 times itself. Then the entire cost model is run using this augmented variable to obtain the augmented value of the cost function. Thirdly, the value of the partial derivative is computed using Equation 29. Next, the value of the partial is multiplied by the uncertainty associated with the variable being considered. This product, when squared, corresponds to one of the terms in Equation 31. The resulting values are added together one by one during each application of the five-step-per-variable process. The last step requires the variable in question to be returned to its original value so that it does not change the results of the computations that follow. After each partial derivative has been computed in this way, the square root of the combined error terms (as in Equation 31) is taken. The resultant uncertainty is then available for recall when the output is generated for any given cost model run.

A delta of 0.00001 was used for the error routine because it appeared to provide at least three or four significant figure reliability. Three or four figures are more than enough when computed uncertainties typically range from 10 to 20 percent or more of the computed cost.

Evaluating Input Uncertainties

A typical 20-township area was selected. Seventeen existing control points were spaced at 10,500 metres. Forty-five new points spaced 5,500 metres apart with a precision of one part in 50,000 between adjacent points were to be positioned. Reasonable 1983 inputs and costs were used. The computed cost was $43,000 ± $5,100, the uncertainty being about 12 percent of the computed cost. The results of this input error variable test are documented in Table 3. This positioning situation is probably on the small side for an optimum application of this technology. The discussion and analysis that follows must be considered in this context. It must also be stressed that each different situation is unique and that the results of this analysis may not be applicable in other situations.

TABLE 3. EXAMPLE CONTRIBUTIONS OF INPUTS TO TOTAL COST UNCERTAINTY

Variable	Input Value	Input Value Uncertainty	% Contribution to Total Error
ROP	1,500 images	200	26.43
CPOP	$150	$25	13.70
AE	0.00002	0.000002	12.58
NSJ	45 points	4.5	12.58
PFAF	1.19	0.2	11.35
SD	5,500 metres	550	8.59
RA	250 km/hr	25	3.42
R	30 km/hr	5	3.24
PDT	0.33	0.05	1.97
RPP	10	2	1.52
CCP	$20	$5	1.34
CAH	$1,000	$50	0.59
NSI	17 points	1	0.53
DCTC	$450	$50	0.47
PR	$350	$50	0.44
CBWN	$15	$2	0.38
TSLT	0.25 hours	0.04	0.24
DUF	2 days	0.3	0.21
PUPT	0.1 hours	0.02	0.10
TMPG	10	2	0.10
CPT	$3	$0.50	0.07
PPT	0.25	0.04	0.06
CCD	$720	$100	0.05
DAC	5,000 metres	500	0.02
PPLD	0.05	0.004	0.02
A	$1{,}865 \times 10^6 m^2$	6×10^6	0.01
NPM	1 copy	0.02	0.01
TRPD	$24	$3	0.00
CPKM	$0.125/km	0.005	0.00
CLT	$10	$2	0.00
TSPT	0.2 hours	0.03	0.00
TLM	0.25 hours	0.04	0.00
FCPG	$1.25/gal	$0.05	0.00
DGT	20 km	5	0.00
SMEC	0	0	0.00*
CMM	0	0	0.00*
TSM	0	0	0.00*

* No monumentation was evaluated for this test.

DATA HANDLING, GEOMETRIC, AND OTHER UNCERTAINTIES

Over 50 percent of the total cost uncertainty is due to variables that significantly influence Equation 28. Rate of image pointing (ROP) contributes over one-fourth of the error, or 26.43 percent. Cost of the data handling office worker (CPOP) influences 13.7 percent of the final cost uncertainty. The photogrammetric final adjustment factor inputs (PFAF), which are directly taken from Ida County project results, contribute 11.35 percent. It might be possible to know the CPOP inputs with significant prior knowledge about an operation. It is unlikely that the reliability of the ROP or PFAF input variables will be known to any greater degree of precision, however. Thus, only a minor total cost error improvement is possible through better control of these three inputs.

The allowable error between the newly positioned points (AE) and number of new points (NSJ) each contribute 12.58 percent to the total cost error budget. New point spacing (SD) contributes 8.59 percent. These three sources account for over one-third of the total cost error in this test situation. A large opportunity to reduce total cost error does exist here. It could be argued that no variability in the AE input should be allowed, and the number of points targeted could be known precisely with careful planning. Additionally, use of a precise grid of PLS monuments (at any given possible spacing) would greatly reduce the total cost error contribution of SD.

Only five of the additional 13 inputs contribute more than 1 percent to the total cost uncertainty. RA at 3.42 percent, *R* at 3.24 percent, PDT at almost 2 percent, RPP at 1.52 percent, and CCP at 1.34 percent comprise this list. These minor contributions do not pose any real problems. Little effort should be directed at improving the uncertainties of these inputs because the significant effort required would be much more rewarded if spent improving inputs that have a larger impact.

Cost Model Error Summary

Ultimately, several of the input variable uncertainties could be eliminated should the cost model require refinement at some later time. The uncertainties of the following input variables have little or no impact on the total cost uncertainty and are candidates for omission: project area (*A*), vehicle rental per day (TRPD), cost per kilometre (CPKM), fuel cost per gallon (FCPG), and the ground distance between the office and the project areas (DGT). Other input uncertainties could probably be deleted but cannot be ruled out without further tests, because a different project could provide a significantly different mix of these apparently minor input uncertainties.

COST MODEL CALIBRATION

The NOS Ada County project was the first of two published projects used to calibrate the high precision photogrammetry cost model. Only the photogrammetric portion, as reported by Perry and Lucas, was considered. Nearly 350 section corners spaced at about 1,610 metres in the northern half of Ada County, Idaho, were positioned in 1978. Seventeen existing stations were available. Fifteen hundred pointings could be conducted in one 4-hour shift (Perry, 1984). One-third of the stations required offset targets and one-fourth required painted targets. Most other inputs were reasonably estimated. The reported costs of \$125,000 (Fritz, 1981) and \$132,000 (Perry, 1984) were matched well by the cost model estimate of \$126,500 ± \$14,800. The values of the different input variables for this test are listed in Table 4. The results compared favorably as they should for this test because the cost model was based on the Ada County project.

Duane Brown's Atlanta project (Brown, 1977) could not be modeled because Brown did not report a cost for that project. Thus, comparison and useful calibration was impossible. Brown did, however, provide cost estimates for a theoretical large-scale project. This theoretical project was used as the second calibration run for this cost model. Twenty-six hundred half-mile spaced points in a 40-kilometre by 40-kilometre area were to be positioned. Thirty existing points spaced 7,000 metres apart were available. Allowable positioning error was set at 1 part in 10,000. Monumentation costs were to be included. Brown's estimated cost (1976) was \$488,000. The cost model generated a cost of \$513,000 ± \$67,000. Brown's estimate was well within the computed uncertainty range. The inputs used for this calibration also appear in Table 4. These inputs reflect 1976 costs and the differences between the NOS and the Duane Brown approach to high precision photogrammetry. Brown, for example, uses a super-wide-angle lens. This means that only one-fourth of the total number of photographs required in the NOS approach are necessary. It also means significantly larger ground targets are needed. The input costs of color prints and black-and-white negatives in the second calibration test reflect such differences.

Both calibrations appear successful. Two significantly different situations have responded well to these evaluations and provided valid comparisons. It is hoped that more projects will be documented in the future to facilitate further verification of this cost model.

SUMMARY

The High Precision Photogrammetry Geodetic Positioning Cost Model is an effective tool for predicting the costs associated with particular areawide positioning applications. The model has a somewhat limited range of applicability because the dearth of current activity makes it difficult to know the true limitations of this technology. Given an area large enough and with enough existing control points to make this method applicable, the cost model is very flexible. This flexibility is expressed by the fact that any one of 37 input variables may be changed to reflect the true situation surrounding a given cost estimate. Flexibility also makes the model quite susceptible to the quality of input data.

The apparent potential of precise photogrammetric geodetic positioning for areawide horizontal geodetic survey networks should be exploited whenever this method appears to be feasible and cost effective. Unfortunately, little advantage seems to have been taken of this breakthrough in photogrammetric technology. It is not clear why this method has not seen wider application. Alternate techniques that appear less labor intensive but require perhaps higher equipment costs seem to be the preferred areawide positioning methods. Perhaps a broader view would change this perception, at least in the short run. The photographs resulting from a precise photogrammetry geodetic positioning project could, for example, be utilized for many other purposes within the context of a developing multipurpose cadastre.

This cost model does not take potential peripheral benefits into account. The user of positioning technology must also carefully weigh all possible additional benefits before selecting an optimum positioning method.

CONCLUSION

The High Precision Photogrammetry Geodetic Positioning Cost Model provides a mechanism for predicting precise photogrammetric positioning

TABLE 4. COST MODEL CALIBRATION TESTS

Input Variable	Calibration Test #1 (Ada County, Ida.)		Calibration Test #2 (Brown's Theoretical)	
AE	0.000031 ± 0.000005	(R)	0.0000952 ± 0.000001	(R)
NSJ	346 ± 5	(R)	2,600 ± 100	(R)
NSI	17 ± 2	(R)	30 ± 3	(R)
SD	1,610 ± 20	(R)	800 ± 100	(R)
CCD	350 ± 50	(E)	120 ± 10	(E)
TMPG	8 ± 1	(E)	15 ± 1	(E)
TRPD	40 ± 5	(E)	10 ± 2	(E)
FCPG	1.10 ± 0.10	(E)	0.50 ± 0.10	(E)
CPKM	0.15 ± 0.03	(E)	0.15 ± 0.03	(E)
R	30 ± 5	(E)	50 ± 10	(E)
PR	230 ± 25	(E)	80 ± 5	(E)
A	$9{,}065 \times 10^5 \pm 1 \times 10^5$	(R)	$1{,}600 \times 10^6 \pm 2 \times 10^4$	(R)
DGT	5 ± 1	(E)	5 ± 1	(E)
SMEC	0 ± 0	(R)	5 ± 0.5	(R)
TSM	0 ± 0	(R)	1 ± 0.2	(R)
CMM	0 ± 0	(R)	20 ± 2	(R)
CBWN	15 ± 2	(E)	5 ± 1	(E)
CCP	20 ± 5	(E)	5 ± 1	(E)
NPM	1 ± 0.02	(R)	1 ± 0.02	(E)
CAH	1,000 ± 50	(E)	200 ± 20	(E)
RA	150 ± 25	(E)	250 ± 25	(E)
DUF	2 ± 0.3	(E)	1 ± 0.5	(E)
PPLD	0.05 ± 0.004	(E)	0 ± 0	(R)
CPOP	180 ± 20	(E)	80 ± 10	(E)
RPP	10 ± 2	(R)	20 ± 2	(E)
ROP	1,500 ± 200	(R)	2,000 ± 200	(E)
CPT	3 ± 0.5	(E)	1 ± 0.1	(E)
CLT	10 ± 2	(E)	0 ± 0	(R)
TSLT	0.25 ± 0.04	(E)	0 ± 0	(R)
TSPT	0.2 ± 0.03	(E)	0.25 ± 0.05	(E)
TLM	0.25 ± 0.04	(E)	0.05 ± 0.01	(E)
PDT	0.33 ± 0.05	(R)	1 ± 0.1	(R)
PPT	0.25 ± 0.04	(R)	1 ± 0.1	(R)
DCTC	450 ± 50	(E)	100 ± 10	(E)
PFAF	1.19 ± 0.20	(R)	1.19 ± 0.20	(E)
PUPT	0.1 ± 0.02	(E)	0 ± 0	(R)
DAC	5,000 ± 500	(E)	20,000 ± 5,000	(E)
Total Computed Cost	$126,500 ± $15,800		$513,000 ± $67,000	
Total Published Cost	$125,000		$488,000	

NOTE: (R) indicates input value taken from or based on applicable references. (E) indicates input value is an educated estimate based on the particular situation.

costs and may be useful to those who must plan areawide control densifications. When used in conjunction with other positioning technology cost models (Crossfield, 1984), this cost model can be used to help select the most cost effective technology for a particular positioning task.

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APPENDIX
ACRONYM DEFINITIONS

A	Area of the project in square metres
AE	Allowable horizontal point positioning error ratio
CAH	Aircraft cost per hour
CBWN	Cost of one black-and-white negative
CCD	Daily monumentation crew cost
CCP	Cost of one color print
CFT	Total flight transportation cost
CLT	Cost of one paneled target
CMM	Total cost of one monument's materials including accessories
CPKM	Ground vehicle cost per kilometre
CPOP	Daily photogrammetric office person cost
CPT	Cost of one painted target
DAC	Air distance from the airfield to the centroid of the project area in kilometres
DCTC	Daily targeting crew cost
DGT	Ground distance from the office to the centroid of the project area in kilometres
DUF	Expected average number of days until flight after all targets are set
EE	Expected error
FCPG	Ground vehicle fuel cost per gallon
MD	Number of 8-hour monumentation days
NCREW	Number of target maintenance crews required
NPM	Number of copies of target identification prints required
NPPC	Number of photos in the primary coverage
NS	Total number of points to be positioned
NSI	Number of existing useable geodetic points
NSJ	Number of new points to be positioned
PDS	Percentage of paneled targets
PDT	Percentage of points requiring double targets
PFAF	Photogrammetric final adjustment factor: amount of final total adjustment and data manipulation time versus the total photogrammetric measurement time
PMEC	Total monumentation equipment cost
PMLC	Total monumentation labor cost
PMRAC	Photogrammetric measurement, reduction, and adjustment labor cost
PMTC	Total monumentation transportation cost
PPLC	Total planning labor cost
PPLD	Percentage of panels lost each day while waiting for flight
PPS	Percentage of painted targets
PPT	Percentage of stations requiring painted targets
PR	Planning cost per day
PUPT	Hours required to pick up one panel
R	Ground vehicle rate of travel
RA	Aircraft speed in kilometres per hour
ROP	Number of photogrammetric image pointings per office person day
RPP	Number of points plotted on maps per hour
SD	Spacing distance between new points in metres
SMEC	Daily monumentation support equipment costs
TCD	Total required targeting crew shifts initially required
TCUP	Ground transportation cost per kilometre
TD	Total targeting time in days
TLM	Average number of hours required to locate one monument
TMDT	Total monumentation distance
TMPG	Ground vehicle miles per gallon
TPCOST	Total cost estimate
TPEC	Total equipment cost
TPHC	Total photograph cost
TPLC	Total labor cost

TPTC	*Total transportation cost*
TPTEC	Total targeting equipment cost
TPTLC	Total targeting labor cost
TPTTC	Total targeting transportation cost
TPUD	Days required to pick up all panels
TRPD	Ground vehicle rental cost per day
TSLT	Average number of hours required to set one paneled target
TSM	Time required to set one monument and its accessories in hours
TSPT	Average number of hours needed to set one painted target
TTCD	Total ground distance traveled during target maintenance
TTD	Total target establishment distance in kilometres

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