NOAA Technical Memorandum NOS NGS-41

A HYBRID METHOD OF MAPPING AND PHOTOGEODETIC CONTROL NETWORK DENSIFICATION

Ron Adler

Rockville, Md.
October 1984

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A HYBRID METHOD OF MAPPING AND PHOTOGEODETIC CONTROL NETWORK DENSIFICATION

Ron Adler[1]
National Geodetic Survey
Charting and Geodetic Services
National Ocean Service, NOAA
Rockville, Md. 20852

ABSTRACT. During the past few years tremendous progress has been made in aerial triangulation by block adjustment with additional parameters. This method has achieved reliability and accuracy not considered possible only a decade ago. This paper postulates that photogeodetic control densification is economically viable, especially when performed in conjunction with well-defined mapping tasks. Satellite geodesy, by means of the NAVSTAR Global Positioning System, is also discussed. This recently operational system is revolutionizing the approach to geodetic control densification by attaining survey results of centimeter-level accuracy.

INTRODUCTION

Densification of geodetic control networks is a never-ending task. The basic guiding principle in geodesy, "From the whole to the part," is as valid today as it was hundreds of years ago. However, "the whole" and "the part" assume different connotations as a function of the size of the area; its degree of development; political, social, and administrative structure; density of population; and many other factors. Thus the classification of geodetic networks by orders or classes is not heterogeneous, and one looks for common denominators to express characteristics and quality measures.

My approach to a quality measure is influenced to a large degree by the precision of observations obtainable with current technologies and by user requirements, which as a rule are difficult to obtain, often unrealistic, and sometimes influenced by subjective considerations. Geodesists, surveyors, and cartographers are often forced by circumstances to assume the role of the user's advocate and anticipate needs based on available resources. This opens the door to abuse, sometimes unintentional, due to a lack of knowledge, but sometimes dictated by subjective considerations of the user's best interests. Such abuses demonstrate the need for a standard that is designed to ensure a common denominator of quality available to the public.

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[1]Permanent address: Survey of Israel, Tel Aviv 61 141, Israel.

This research was conducted in April-August 1983 when the author was a Senior Visiting Scientist at the National Geodetic Survey under the auspices of the Committee on Geodesy, National Research Council, National Academy of Sciences, Washington, D.C.

Geodetic standards may be characterized as either guidelines or ordinances. The United States favors the first approach. Classification standards for Federal geodetic surveys are mandatory only within the National Geodetic Survey (NGS) of the National Ocean Service, NOAA, the Federal organization charged with responsibility for establishing and maintaining the national horizontal, vertical, and gravity control networks. Practitioners outside NGS are encouraged to adhere to the standards through the offer to have their surveys classified by NGS for compliance with official standards. However, it appears that NGS is seldom asked to perform this service for photogrammetric control densification.

In many countries geodetic classification standards are mandatory. Often the surveyor must obtain a government license to perform a survey and then comply by law or by ordinance to the prescribed standards. Various penalties are exacted for noncompliance. It may also be mandatory to connect local surveys to a national network if they exceed a certain minimum area and if national network stations are available within a certain specified distance of the survey. These factors, combined with the size of the area being surveyed, result in much greater emphasis being placed on lower-order geodetic networks as an infrastructure for cadastral and engineering development projects and for large scale national mapping.

In the United States, the size of the country and its Federal structure dictate that the NGS is principally concerned with higher-order geodetic control, i.e., first-order and second-order surveys. Third-order control, although officially recognized, is patchy in coverage, local in character, and of minor concern. Fourth-order control is not categorized and is estimated to be of only 1:3,000 accuracy. It is possible that less attention may be paid to lower-order control in the future as a result of new technology.

Tremendous progress has been made in aerial triangulation in recent years, achieved through block adjustment with additional parameters. These techniques have produced surveys of excellent reliability and accuracy which were not possible only a decade ago. Parallel with this effort has been the development of geodetic positioning by means of the NAVSTAR Global Positioning System (GPS). Now operational, the system is achieving centimeter-level accuracy and will revolutionize the approach to geodetic control densification.

This paper explores the idea that photogrammetric control densification is an economical surveying method in those places where geodetic control is particularly intensive, or where the mapping task is well-defined.

STANDARDS AND SPECIFICATION FOR GEODETIC CONTROL

Geodetic surveying standards are established with the user in mind as a measure of quality of the final product, e.g., horizontal coordinates and elevations. In the United States, the Federal Geodetic Control Committee (FGCC) sets standards and recommends compliance where positional values are required in the national system, or where very precise relationships between control points are needed. The FGCC classification standards of accuracy are a measure of quality of the geodetic control, and are accompanied by specifications that outline the precision necessary to achieve the accuracy prescribed by the standards. The sharp distinction between standards and specifications is described by Milbert (1983).

The horizontal classification standard is defined as the minimum relative accuracy of distance between directly connected adjacent points expressed in the form 1:a, where a is a survey distance accuracy denominator. The full explanation of the underlying statistical theory and the derivation of the survey distance accuracy denominator are given by the Federal Geodetic Control Committee (1984).

Table 1 lists the standards for establishing control for the National Geodetic Horizontal Network (FGCC 1984). Detailed specifications covering the uniform classification standards given in table 1 are published by the Federal Geodetic Control Committee for each of the following horizontal survey techniques: triangulation, traverse, inertial surveying, satellite Doppler positioning, and photogrammetry (FGCC 1984).

Table 1.--Accuracy requirements for the National Geodetic Horizontal Network

Classification	Distance accuracy	Specifications for minimum station spacing (km)
First order	1:100,000	15
Second order, class I	1: 50,000	10
Second order, class II	1: 20,000	5
Third order, class I	1: 10,000	0.5
Third order, class II	1: 5,000	0.5

The new Federal Geodetic Control Committee (1984) publication is user-oriented and, in my opinion, will encourage the surveying community to have new control surveys classified in compliance with the standards. I believe these standards will serve as a guideline for many other countries to restructure and revise their existing regulations. It will especially encourage and legitimize the inclusion of relatively new techniques for extending horizontal control, such as photogrammetry, satellite Doppler positioning, and inertial surveying.

A key sentence in the FGCC publication (FGCC 1984) typifies the importance of the applications approach fostered by NGS: "It is not observation closures within a survey which are used to classify control points, but the ability of that survey to duplicate already established control values." What can better express the importance of the control networks and the multitude of activities they support, including precise engineering and cadastral surveys!

PHOTOGEODESY

Densification of horizontal geodetic control by analytical photogrammetric techniques has received ample and well-deserved attention in the scientific community. Its acceptance by the user community, however, has been slow and reluctant, with some notable exceptions, e.g., Brown (1971, 1973, 1977a, 1977b) Hvidegaard (1976), Slama (1978), Kruger (1980), Lucas (1981) and El-Hakim (1982).

Official recognition of analytical photogrammetry as an approved technique for the extension of geodetic control has been surprisingly slow, not only in the

United States but practically throughout the world, especially in view of the excellent results reported from various tests and actual projects. The new FGCC specifications will include photogrammetry for the first time, coming perhaps too late for optimum advantage as new technologies begin to replace it.

According to Grun (1982), certain basic requirements must be fulfilled in high-accuracy applications of modern photogrammetric bundle block adjustments:

- Use of targeted points.
- Flights with 60 percent sidelap or 20 percent sidelap and cross flights.
- Relatively dense perimeter control in planimetry and relatively dense grid of height control points.
- Measurement of image coordinates and application of rigorous block adjustment, including a method for systematic error compensation. Self-calibration is recommended.
- Sophisticated gross error detection strategy.

The new Federal Geodetic Control Committee specifications (1984) provide adequate provisions for fulfilling these requirements.

The following comments seem appropriate regarding the FGCC approach:

1. Horizontal control points must be one order higher than the new (densification) survey. Thus, photogrammetric extension is limited to second- and third-order control, except for those cases when it can be upgraded if meeting the standards for higher accuracy. The specifications require that all horizontal geodetic control be targeted. For second-order control, pass points have to be targeted as well; however, third-order control does not require targeting of pass points. NGS uses orange-colored discs for targeting. The camera lens is designed for optimal resolution at a narrow band of orange light in the visible spectrum. This design minimizes aberrations for that particular wavelength and ensures targets will be presented with the sharpest definition. Use of uniformly colored targets also minimizes variation of lens distortion with color.

2. A 66 percent minimum forward overlap is required. A 66 percent sidelap is required for second-order control with a minimum of nine intersecting rays per point. For third-order control, a 33 percent sidelap is required with a minimum of three intersecting rays per point.

3. A minimum of eight horizontal control points are to be spaced about the perimeter of the survey at no more than seven air bases apart.

4. The images are measured in a comparator with a least count of 1 μm. Regarding compensation of systematic error, a number of specifications exist requiring the application of calibration data in correcting measured image coordinates. Reseau measurements must accompany second-order, class I measurements, whereas only the fiducials have to be measured for other classes.

5. The measured data are snooped for blunders, and weights are checked through analysis of the postadjustment estimate of the variance of unit weight.

The root mean square error of the adjusted photocoordinates (in micrometers) should not exceed the following specifications:

Second order		Third order	
Class I	Class II	Class I	Class II
4	6	8	12

The best empirically proven accuracy levels reported by Ackermann (1982) and Grun (1982) are just below the 3 μm level for planimetric points, with the best vertical accuracy on the order of 0.003 percent of the flying height. Thus the case in behalf of photogeodesy is proven and its status officially recognized as a reliable technique for the extension of horizontal control.

IMPLICATIONS OF THE GLOBAL POSITIONING SYSTEM

On rare occasions a new technology appears that starts a new era in geodetic science. Such was the case with electronic distance measurement instrumentation in the 1950's and 1960's. It completely revolutionized land surveying concepts. The same was true of satellite Doppler positioning. In each of these instances a cycle was initiated which began with the conceptual application of a known physical phenomenon, followed by a first generation of instruments that proved the concept but which was not readily accepted by the user community. In the last stage the instruments were made simpler, less costly and more portable, and were finally accepted routinely by the users.

The NAVSTAR Global Positioning System is a modification and extension of the Doppler TRANSIT system, designed to provide continuous three-dimensional position fixing and incorporation of high-stability time standards. Initiation of a full scale development program was approved in 1973 by the U.S. Department of Defense after a period of concept validation. The plan envisaged deployment of 24 satellites (later reduced by budgetary constraints to 18) by 1989. Bossler et al. (1980) detail specific characteristics of the system and its potential for geodetic positioning; Remondi (1983) and Bossler (1983) describe developmental status.

Currently, several geodetic receivers are being developed, all capable of subcentimeter-level relative geodetic positioning. The potential implications of GPS for various geodetic purposes are compelling, with particular stress on cost effectiveness. The status of current technology can be summarized as follows:

1. Six GPS satellites are now in operation, of which three or four are visible from two to six hours each day.

2. By 1989, 18 GPS satellites are expected to be available for observations (perhaps more), making round-the-clock observations a reality.

3. Recent FGCC tests show that subcentimeter relative accuracy is realistically achievable over short base lines (0.4-1.3 km), varying between 1:50,000 and 1:500,000. Tests for long base lines (8-42 km) show relative differences on the order of 1:500,000. This is remarkable because the terrestrial base line lengths used as a standard for comparison were estimated as being no better than 1 ppm at the 1-sigma level. The mean of azimuth differences for the long base lines was 0.41" with an rms of 1.08", which is within the 2-sigma estimate for terrestrial azimuths.

The instruments were vehicle mounted, but the antennas could be placed on the point of observation up to 30 m away from the receiver. Results of the tests and demonstration are described by Hothem and Fronczek (1983).

4. Observation time required for measuring base lines less than 5 km long is 2 to 3 hours, with essentially one person operating one receiver. It is estimated that three to four stations per day could be observed on a single work shift basis with deployment of the full 18-satellite constellation. The addition of a third receiver to the basic two-instrument configuration would double productivity.

5. Availability of access to the highly precise P-code and/or the satellite ephemerides by the civilian and international user community is not yet clear, subject to limitation of availability or accuracy degradation as dictated by security considerations. This undoubtedly is a problem which has to be carefully considered before a decision is made to commit users outside of the U.S. defense establishment to a long-term policy of geodetic control densification based on GPS. In addition, for relative positioning by interferometric methods, independence from the P-code has already been achieved by treating the code signals as random noise, similar to the VLBI techniques.

6. Traditional geodetic field methods are labor intensive and require intervisibility between stations. Assuming the selective availability problem can be satisfactorily solved and anticipating that the usual cycle of competition drives down the price of receiver sets (coupled with increased portability of equipment), GPS will become the most viable technique for geodetic control densification.

Thus, we are compelled to recognize the potential implications of GPS and reconsider our approach to control densification policies for various geodetic purposes with particular stress on the analysis of cost effectiveness.

DENSIFICATION OF GEODETIC CONTROL COMBINED WITH MAPPING

In photogeodetic applications targeting of all existing geodetic control as well as the pass points representing the densification are important in achieving maximum precision. With artificially marked and transferred points the estimate of the precision of observations may deteriorate by as much as a factor of 2.

Another aspect of great importance is the geometric configuration, where the 66-percent forward overlap and 66 percent side overlap ensure nine ray intersections per point. This, combined with the required density of control extension, limits the flying height, as can be easily seen from the expression:

$$H = if/(10.3)a$$

where H is flying height above ground in meters,
f is focal length of the camera in meters,
a is a photograph format with dimensions in meters, and
i is the required density of control extension in meters (appropriate length of air base).

Both Grun (1982) and Ackermann (1982) agree that the σ_o^{xy} at the photoscale for a bundle block with self-calibration is estimated at 2.5 μm at the photoscale. Table 2 shows the estimated standard deviation of ground coordinates, using a 3 μm value. The typical control densities use a standard wide-angle lens cone with 0.152 m focal length and 23 x 23 cm standard format.

Table 2.--Accuracies achievable in photogrammetric control densification

Control extension to density, i (m)	Flying height, H (m)	Resulting photoscale	σ_o^{xy} 3 μm at photoscale (m)	σ_o^{h} 0.005% of flying height (m)
1,600	3,600	1:24,000	0.07	0.18
800	1,800	1:12,000	0.04	0.09
400	900	1: 6,000	0.02	0.05

The results obtained in an operational environment in the Ada County, Idaho project, performed by the National Ocean Service and reported by Lucas (1981), show that these accuracy estimates are clearly achievable. It is worth noting that Duane Brown envisioned such accuracies some 10 years ago when he reported on an urban densification project (Brown 1977b). Another precise photogrammetric densification of an urban control network is reported by El-Hakim (1982).

The accuracy of vertical control extension in a bundle block adjustment with self-calibration is estimated by Grun (1982) at 0.003 percent of the flying height and by Ackermann (1982) at 5 to 10 μm at the photoscale. As a conservative estimate, table 2 gives the ground values equivalent to 0.005 percent of the flying height. Standard deviations of this magnitude are assumed to be more than acceptable for discrete points of elevation for digital elevation models as well as for conventional mapping. The most demanding standards required for minimum vertical contour intervals should be five times the standard deviation of the elevation of a discrete point.

Densification policies are influenced by many factors, especially economic and political considerations and available techniques. When considering the most appropriate approach to follow, various distinguishing features of densification surveys should be considered:

1. Densification for the purpose of establishing or extending the National Geodetic Reference System in an area. This is clearly a case of providing geodetic control for purposes not clearly defined within the framework of national policy, i.e., to provide nearly uniform coverage of the country for a multitude of anticipated needs for geodetic control.

2. Densification within a well-defined local area, urban or rural, which may provide a locally available reference system of prespecified density for development of cadastral purposes, e.g., an infrastructure for a computerized land data system, tied into the national geodetic networks. This would be an ideal situation where any prospective user could expect to find control available for a particular purpose within a short distance anywhere in an area. Such an approach has been discussed by El-Hakim (1982) and others.

3. Densification to provide control for mapping operations of a specified nature and scale: topographic, multipurpose cadastre, engineering projects, and others. Densification is usually undertaken in the planning stage for a major development in an area and remains to serve subsequent stages as well as other purposes in the future. The mapping products are produced to conform to prescribed standards of accuracy.

It quickly becomes noticeable that photogrammetric procedures for mapping are different than procedures employed for photogrammetric densification in extension of geodetic control. As far as can be ascertained, almost all of the various instructions and guidelines for mapping are derived empirically. There is no universal standard mapping scale or standard contour interval. Many countries and agencies have developed their own.

An approximation can be made of typical map scales and their corresponding contour intervals produced by photogrammetric methods. Based on various approximations, different procedures attempt to achieve economy of operation, combined with certain standards of accuracy, in producing the final product. Such procedures must take into consideration certain limitations of photogrammetric mapping. In most cases empirical guidelines are based on the relationship between the focal length, the flying height, and the map scale with its accompanying contour interval, and the instrumentation used in the photogrammetric restitution and plotting. It is obvious that the guidelines and instructions are aimed at satisfying an accuracy standard in the final product--the map.

For horizontal accuracy, the U.S. National Map Accuracy Standards (USNMAS) require that 90 percent of the points tested (well-defined points of detail) be within 1/50 inch, or 0.5 mm, at scales of 1:20,000 and smaller; and within 1/30 inch, or 0.85 mm, at scales larger than 1:20,000. For vertical accuracy at all published scales, 90 percent of the elevations tested shall be within one-half of the contour interval. The positions and elevations of the points tested are compared with positions and elevations determined by surveys of a higher accuracy for the purpose of determining compliance with the USNMAS.

It would be reasonable to assume that at the time these standards were published in 1947 by the U.S. Bureau of the Budget the intention was to check photogrammetric mapping by field surveys. It is not the purpose of this paper to analyze the USNMAS or scale factors of 1:20,000 and less, which are part of the U.S. National Mapping Program providing nationwide standard topographic map series coverage. It is my intention to consider scales larger than 1:20,000 where the applications are mainly used for urban and rural development, planning, engineering projects, and cadastres.

The need for preserving an unambiguous standard of accuracy for maps diversified in scale, contour interval, and content, as an alternative to USNMAS, is outlined by Merchant (1983). The important point of the Engineering Map Accuracy Standards

(EMAS) is that the evaluation of a map for accuracy is based on the assumption that an average bias systematic error has been removed from the discrepancies between the map values and the checked survey values. It is presumed that the altered discrepancies are normally distributed. The comparison (check) is made on well-defined features, omitting those which may have been subject to the effects of symbolization or generalization. The resulting σ_o is estimated as the standard deviation from the mean deviation.

The comparison is then between the position of the mapped feature obtained through measurements on the map and the position determined independently by a survey of "adequate accuracy." This slightly unfortunate term represents a check survey which is estimated to be at least equal in accuracy to that of the control survey from which the map was compiled. This is one of the main reasons why the process of control extension for mapping should also include a provision for checking the final map for compliance with the prescribed standards (USNMAS, EMAS, or any other standard).

Another important aspect of densification is its impact on the future potential of mapping as advocated by Brown (1977b). There has always been a clear separation between mapping and control extension and between the analog and analytical photogrammetry used to produce them. However, with the development of the analytical plotter, the latter distinction is melting away and I believe the former will quickly follow.

Improvements in recent years in analytical plotters with associated hardware and software have resulted in lower prices. There seems to be little difference between the price of an analytical plotter and a good analog instrument, both equipped with advanced plotting tables. The analytical plotter has proven itself not only in control extension, but also in large scale mapping. Today software mapping libraries assist in producing high quality maps while at the same time providing the option of graphical or digital products, or a combination of both, tied into densified geodetic control. The increased mapping potential of the analytical plotter permits a continuous correction of all points within the model, resulting in the increase of a C-factor* rating for analytical plotter mapping to at least 4,000. The plotter utilizes corrections for film deformation and for residual systematic error obtained from bundle adjustment with self-calibration within the densification.

It is difficult today to draw a line between digital and graphical mapping. In many ways digital mapping is a form of densification, where an area is covered by a dense, albeit irregular, net of discrete points, and the coordinates are of an accuracy almost equal to that of nonpaneled densified control. In many instances digital mapping is executed for cadastral purposes, where the interest lies in coordinates of lot corners, points of change of direction along nonstraight line boundaries, corners of buildings, fences, manholes, intersection of roads and paths, and other features. These are the well-defined points of detail mentioned in the accuracy standards for a particular map. Considering this, purely graphical accuracy is of secondary or even lesser importance. No extensive investigations are currently available to evaluate reliably the deterioration of accuracy of the well-defined points of detail in natural features as opposed to presignalized densification points.

*The photographic flying height divided by the C-factor of an instrument is the contour interval that can be attained from the photo/plotter combination.

When exploring the combination of photogeodetic control densification with photogrammetric mapping, certain criteria acceptable for both tasks must be satisfied before showing that the proposed combination is cost-beneficial. Table 3 lists a combination that can be derived for different map scales. The first two columns show the map scales in photogrammetric mapping with their associated contour intervals. Choice of a contour interval for a specific mapping scale depends on terrain and the envisaged purpose of the map.

The typical flying height is the result of planning based roughly on the C-factor associated with the stereoplotter to be employed on the mapping task. For scales of 1:1,000 and larger a "first-order" stereoplotter with a C-factor of 2,000 would be appropriate, for scales of 1:2,500 through 1:10,000 a "second-order" stereoplotter with a C-factor of 1,500, and for smaller scales a "third-order" stereoplotter with a C-factor of 1,000. These are of course empirical approximations based on practice.

As mentioned previously, aerial triangulation with bundle block adjustment for the purpose of densifying geodetic control requires geodetic stations along the block perimeter at spacings no larger than seven air bases apart. Column 7 of table 3 shows a six air base spacing, which for control densification would be the density of the existing network. Column 8 shows the length of the air base for various flying heights associated with mapping, and is the new density achieved through control densification by photogeodesy.

Table 3.--Combination of conventional mapping with photogeodetic control densification

1	2	3	4	5	6	7	8
Map scale	Map contour interval (m)	Typical flying height (m)	Resulting approx. scale 1:	Estimated $\sigma_o^h \cong$ 0.005% of flying height (m)	Minimum contour interval $\cong 5\,\sigma_o^h$ (m)	Old density (existing geodetic network) 6 air bases (m)	New density (length of air-base) (m)
1:250	0.25	500	3,300	0.025	0.125	1,500	250
1:500	0.25	500	3,300	0.025	0.125	1,500	250
	0.5	1,000	6,500	0.05	0.25	3,000	500
1:1,000	0.5	1,000	6,500	0.05	0.25	3,000	500
	1.0	2,000	13,000	0.1	0.5	6,000	1,000
1:2,500	1.0	1,500	10,000	0.1	0.5	4,800	800
	2.0	3,000	19,000	0.15	0.75	9,000	1,500
1:5,000	2.0	3,000	19,000	0.15	0.75	9,000	1,500
	2.5	3,750	24,500	0.2	1.0	10,800	1,800
				Assumed minimum existing density			
1:10,000	2.5	3,750	24,500	0.2	1.0	10,800	1,800
	5.0	7,500	49,000			22,200	3,700
1:25,000	5.0	5,000	32,000				2,400
	10.0	10,000	66,000				5,000
1:50,000	10.0	12,000	80,000				6,000

Now the derivation of a combination of photogeodetic control densification with specified mapping tasks becomes simple:

1. Densification from approximate spacing of 10 km down to 1,600 m, combined with mapping at 1:10,000, 1:5,000, or even 1:2,500 (2-meter contour intervals).

2. Densification from 5 km spacing down to 800-1,000 m spacing, combined with mapping at 1:2,500 or 1:1,000 (1-meter contour interval).

3. Densification from 3 km spacing down to 500 m, combined with mapping at 1:1,000 or 1:500 (0.5-meter contour interval).

The very large scales of mapping for 1:250 and 1:500 scale with a 0.25-meter contour interval are excluded from the combination because such mapping is usually carried out for specific local tasks and confined to areas of limited extent. The small scales (bottom four rows of table 3) are excluded from the combination because the control density of approximately 10 km exists practically everywhere.

The combination of densification with mapping, as outlined here, has a number of advantages:

1. No additional photography is required.

2. No additional ground control is required.

3. Excellent quality of planimetry is ensured.

4. Excellent quality of altimetry is ensured (see table 3, column 5, for the estimated accuracy σ_o^h of discrete elevation points and column 6 for the minimum achievable contour interval $\approx 5\ \sigma_o^h$).

5. Settings for orientation of stereoplotters for mapping can be precomputed from the block densification data.

6. Mapping and densification can be achieved within a very short period, often an essential requirement for local purposes.

ECONOMIC CONSIDERATIONS

Photogrammetric densification is economical only when the area under consideration is to be covered by a dense net of discrete points. Such a situation occurs in digital mapping, of which cadastral mapping is a prime example.

Geodetic control required for densification specifies a density of not less than seven bases apart along the perimeter of the area. For the Ada County, Idaho project, the total length of the perimeter was approximately 200 km (125 miles). With the approximate length of the air base being 1,600 m (1 mile), the number of geodetic control stations required would have been 17. This was the exact number utilized in the project (nine existing geodetic stations and eight added for the specific purpose of controlling the block).

The cost of a first-order geodetic station established by conventional terrestrial techniques is about $9,000. Using the GPS technique, with limitations pertaining to the available observation time and the relatively high cost of receivers, the cost per point would be approximately $1,500. As more satellites become available for observation, and competition brings prices down, manufacturers will gradually recover their developmental costs. It is anticipated that the price of establishing a point by GPS may be reduced to approximately $600--less than one tenth the cost of conventional terrestrial geodetic control.

The Ada County project was, in a way, cadastral in nature although it was not presented as such until now. The requirement for some 380 section corners is similar to determining boundary points in cadastral blocks or parcels. Were the requirement stated as densification of the whole area to 1,600-meter spacing, it would have involved approximately 420 stations, which is close to what was done within the project.

The approximate costs for the Ada County project were as follows:

Geodetic control (existing and added)	$ 100,000
Planning, reconnaissance, coordination	40,000
Targeting (section corners)	130,000
Photographic flights (450 photos)	35,000
Mensuration	120,000
Data reduction	150,000
Miscellaneous expenses	25,000
Total	$ 600,000

If this task had been accomplished by field traversing, it would have involved some 1,050 km of traverses, by a conservative estimate. To achieve homogeneous accuracy, considerable redundancy would have been necessary, requiring that each interior station be reached by a pair of independent traverses and the entire network adjusted as a whole. It is also doubtful whether such large spacing could have been preserved for the traverse segments because of the problem of intervisibility.

The estimated cost for a second-order accuracy traverse with 1,600-meter spacing is approximately $1,400 per kilometer, resulting in $1,470,000 for the densification project. The field survey densification, therefore, would have been more than twice as expensive, in addition to the longer duration. It is also doubtful whether such a large spacing could be preserved for the traverse segments because of intervisibility problems.

On the other hand, the inclusion of another 400 points in the area of the photogrammetric densification would add only 25 percent to the total cost, if they were untargeted natural features. This would involve no additional geodetic ground control, no additional photography, no photogrammetric mensuration beyond the additional densification points, and only a small increase for data reduction. Actually, each additional 400 points of this kind would add only 25 percent to the cost. While the cost of the first 400 densification points is competitive with the cost of a Global Positioning System (GPS) survey at today's prices, the cost of photogrammetric densification is not likely to decrease so dramatically with time as has been predicted for GPS. However, as the density of positioned points increases, the cost of positioning by GPS will rise at a greater rate than photogrammetic densification. There is a cross-over point on the cost versus density curve that will determine which applications should be accomplished with GPS and which can be accomplished more economically with photogrammetry.
Although the above figures cannot be regarded as entirely accurate, having been

arrived at by the author from data not fully verified, they nevertheless represent a realistic estimate and generally agree with the cost breakdown of a hypothetical project of photogrammetric densification given by Brown (1977b).

Many types of cadastral mapping can be viewed as densification of geodetic control. Cadastral mapping is becoming increasingly digital in character. There is a growing requirement for the definition of boundaries by coordinates and tying the relevant boundary points to the control network, so that they can be recovered whenever the need arises. The importance of discrete points is not confined to cadastral mapping, but extends to large-scale mapping in general, including engineering applications. It should also be remembered that there is a degradation of positional accuracy involved in photogrammetric plotting of detail on the order of at least twice the rms of the discrete points. There is also a degradation of accuracy involved in converting graphical data to digital form through the process of digitizing.

I believe that the graphical accuracy of the map product will gradually decrease in importance since the map will serve only to provide a general, interpreted, and symbolized picture of the terrain. It will serve as a key to the stored digital values of the discrete planimetric and altimetric points.

I also believe that cartometry will become extinct. It is the digital values that create data bases and permit relevant mutations. Mapping at scales of 1:20,000 and smaller is seldom subject to mutations of considerable extent. It is often a one-time operation with few revisions, seldom justifying automation. However, large scale maps, especially those prepared for cadastral and engineering purposes, are associated with mutations as the result of new subdivisions, building construction, highway construction, or even agricultural land use. They are prone to mutations because they were prepared with mutations in mind. Here, both the digital data collection and the automatic plotting/replotting certainly justify and even demand automation.

CONCLUSION

When performed in accordance with FGCC specifications, the photogrammetric bundle block adjustment with self-calibration is capable of achieving positional accuracy of 3 mm at the photoscale and 0.003 percent of the flying height in control densification. This has been proven in theoretical studies, field tests, and operational conditions.

The bundle block would also serve well for the purpose of obtaining digital elevation models, either as a basis for contouring or for various planning applications in engineering (highway and construction), irrigation, and other projects. The accuracy of 0.003 percent of flying heights compares favorably with trigonometric heights and tachometry. Vertical control can also be used in checking for compliance with mapping accuracy standards.

Photogrammetric control is homogeneously accurate throughout the block area and is particularly attractive when a dense network is to be established. Control surveys performed with GPS are capable of achieving centimeter positioning accuracies, as proven by tests performed under operational conditions. Current reservations pertain mainly to the possibility of limited availability of the equipment, danger of prohibitive user fees, high cost of receivers, and the current limited observation periods (only six satellites are now in operation).

It is expected that the system will be fully operational in 1989 with a minimum constellation of 18 satellites, creating round-the-clock, worldwide capability of three-dimensional positioning. The availability of GPS is not likely to be limited, as the circle of civilian users dependent on the system may reach tens of thousands.

For tasks involving densification of geodetic control, where the reduction in the average distance between stations is on the order of six to one, GPS techniques are likely to become increasingly cost effective. The cost of $9,000 per station established by conventional terrestrial means is excessive when compared to today's figure of $1,500, or the future projected estimates of $600 per station for GPS. GPS receivers are operated by one person and are particularly cost-beneficial when used in configurations of three or more. There is a limit, however, to the density of control that can be established economically by GPS, and from this limit to the extreme, which is mapping, photogrammetric densification will be preferred for positioning control.

Extension of horizontal control by analytical photogrammetry is very effective when combined with mapping operations. The same photography can be used and instrumental settings and correction parameters obtained as a byproduct of aerial triangulation. The term mapping (scale larger than 1:20,000) includes those cases where the graphical product may be of secondary importance and the principal requirement is to determine the position of a large number of discrete points within an area, such as section corners, cadastral boundaries, public utility key stations, or well defined points of detail for the purpose of checking compliance with map accuracy standards.

Vertical control extension by photogrammetry will serve extremely well for mapping, remembering that the minimum contour interval is five times larger than the standard deviation of densified control, which is well within the achievable accuracy limits.

I believe that the combination of control densification with digital or graphical mapping is cost effective and ensures homogeneous accuracy within a defined area, thus providing an answer not only to the initial task but also serving as a durable infrastructure for multipurpose cadastres in the future.

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