Aerial Photogrammetry: State of the Industry in the US

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This article attempts to summarize, in a general way, the current status of the photogrammetric industry in the U.S. in early 1993, particularly as it applies to the commercial workplace. The transition from mechanical and analytical stereoplotters to softcopy raster workstations, and what the future may hold for photogrammetry, are discussed.

For many years photogrammetry (making measurements in photographs) was undertaken using a wide variety of mechanical and optical high-precision instruments capable of making measurements to an accuracy of ten microns at photo scale. Along came computers in the 1960s and 1970s, spurring the development of analytical stereoplotters capable of measuring accuracies of two microns. In the past five years or so, two developments have had a large influence on photogrammetry namely — GPS and the ability to handle raster data. In a generic way, this paper discusses the different procedures involved in creating modern digital maps using photogrammetry.

The classical ground control techniques of traversing and leveling are still widely used in the conventional survey. The National Geodetic Survey (NGS) requirements for blue-booking the results have set excellent standards which many cities and counties are using to ensure high quality monumentation and survey accuracies, while densifying their control monuments in their own geographical areas.

Aerial photo at 1 in. = 275 ft. (1:3300)

GPS (Global Positioning Systems) has revolutionized ground survey procedures for creating ground control points for photogrammetry, resulting in higher and more predictable accuracy, and lower cost. Not only can GPS be used for horizontal control, but when proper geoidal modeling procedures are used, accuracies of 0.2 feet in elevation can be achieved, good enough for two foot contour mapping.

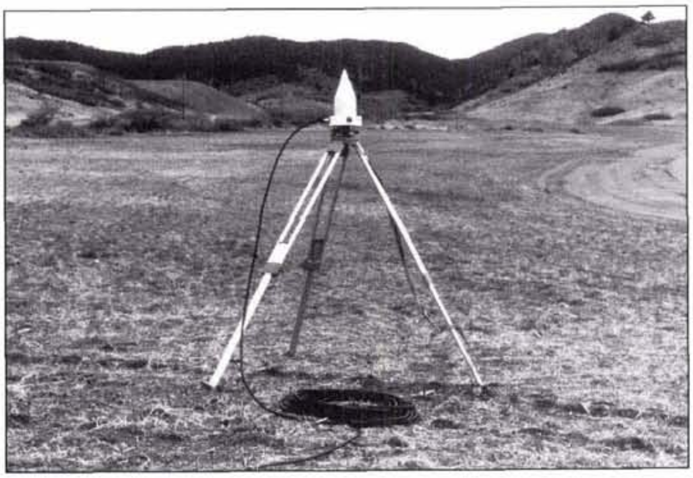
The use of airborne GPS will have a large impact on photogrammetric mapping projects which have the following requirements:

- no need for extensive ground monumentation
- remote areas with limited road access
- relatively small scale photography, where control points are far apart

Airborne GPS uses an onboard receiver to provide X, Y, and Z coordinates for the camera lens at the instant of exposure. Using specialized procedures for elimination of systematic errors, accuracies of 0.4 feet (10 cm) are possible which is good enough for five foot, or one meter, contour mapping. The technique demands high coordination between survey crews and flight crews as ground GPS stations must receive signals *simultaneously* with the aircraft station. In order to stabilize the final bundle adjustment of the photography, cross-strips are flown across each end of the block, perpendicular to the flight lines of the mapping photography. Using this technique, *only four ground GPS points* would be needed for a rectangular block of as many as two hundred stereomodels, although more ground points should be available as checks.

Electronic leveling is another new ground survey technique which is proving to be superior to conventional leveling methods in speed and accuracy. It uses bar-coding technology similar to that used in supermarkets. Recently, in Fairfax County, Virginia, over 950 miles of levels resulted in first-order accuracy even when third-order was specified. Field crews averaged 4.7 miles per day, per crew.

Most projects are currently being compiled using the North American Datum 1983 (NAD83) Coordinate System instead of NAD27. Some projects (e.g. Fairfax Co., VA) are using the new North American Vertical Datum 1988 (NAVD88) as a ba-



A GPS receiver.

sis for vertical control instead of the National Geodetic Vertical Datum 1929 (NGVD29). It is important for the photogrammetrist to recognize that when transforming projects from NAD27 to NAD83, care must be observed using NGS software such as NADCON, which may not be sufficiently precise to maintain accuracy standards at 1"=100' or larger. When in doubt, the use of a Helmert transformation on local NGS monuments whose coordinates can be derived in both systems, is advisable.

Currently, most local governments use coordinates in feet, while federal agencies use metric coordinates. One local government (City of Omaha, NE) has recently chosen to use metric coordinates for its GIS in order to comply with forthcoming regulations for the use of metric standards in federally-funded construction projects. Their maps will be 1:1 000 scale with 1 m contours.

The latest cameras from Wild and Zeiss are masterpieces of modern technology with new and better lenses, forward motion compensation to allow longer exposure times so that higher resolution film can be used, gyro-controlled camera mounts to limit side motion for the same reason, and GPS connections to record the GPS signal at the exact moment of the center of instant of exposure.

Airborne navigation is also making major advancements, by using the GPS receiver connected to the camera as a navigational aid. It is now possible (although by no means widely usable) to determine the position of every photograph center before the flight occurs, and use the GPS information to fly along precise flight lines, automatically opening the camera lens as soon as the aircraft reaches the closest possible location to the pre-planned coordinates (probably within 100 feet). This will result in blocks of photographs where the photo centers are in a perfectly symmetrical pattern, making automatic aerial triangulation much more straightforward.

Black and white photography remains far more popular than color as it is considerably less expensive. While color may have a slight advantage in seeing the ground under trees, there does not appear to be any difference in accuracy. With the advent of raster technology, it should be remembered that true color requires three times more storage capacity than black and white imagery.

Most major mapping projects utilize bundle adjustment solutions, but as yet, very few commercial mapping companies use more advanced aerial triangulation procedures, such as self-calibration of systematic errors to improve accuracy. Current conservative planning of ground control patterns calls for horizontal control points positioned about four model base lengths of distance around the perimeter of the block, this being the minimum for planimetric vector or raster mapping. For contour or accurate DTM mapping, vertical control points at four-model intervals are necessary, on each side of each flight line.

Using these parameters with 1"=500' (1:6,000) scale photography on the Fairfax County, Virginia project, the following accuracies (Table 1) were achieved on independent control points, i.e., points not used as control in the adjustment. Note that this was achieved in a commercial, but carefully monitored, environment.

With higher flown photography where systematic errors are greater, the improvement with self-calibration would be more noticeable.

The last few years have seen acceptance of the new National Map Accuracy Standards (NMAS) for digital mapping. The original NMAS standards are equivalent to the new Class 2 standards, and the new Class 1 standards are about twice as high as Class 2.

Stereoplotters have traditionally been rated into four separate categories, with the C-factors (flight height required divided by contour interval).

Table 2 is not intended to be exhaustive. In general, first-order plotters are seldom used nowadays, having been replaced by analytical plotters, while third-order

TABLE 1

	Conventional Bundle Adjustment		Bundle Adjustment with Self-Calibration	
	rms (feet)	rms (microns)	rms (feet)	rms (microns)
Horizontal Accuracy	0.29	14.4	0.27	13.4
Vertical Accuracy	0.33	16.1	0.29	14.4

TABLE 2

Category	Stereoplotters	C-Factor (Federal Standards)
Analytical	BC-1, P-1, Traster, DSR	2,500
First Order	A-10, Planimat, Stereometrograph	2,100
Second Order	PG2, AG1, B8-S, Santoni IIC	1,800
Third Order	Kelsh	1,200

It is important to recognize to what extent raster technology will impact digital mapping.

order plotters should never be used for accurate mapping. Analytical plotters are considerably more accurate than second-order plotters, but the latter are still widely used.

It is important to recognize to what extent raster technology will impact digital mapping in the future. Computer technology is advancing so quickly that the integration of raster files with vector files is now being implemented, and this trend will certainly continue.

Photogrammetry has changed from purely manual techniques in the early 1980s to being almost purely digital. Over the past six years, some very complex major mapping projects have been successfully completed in cities and counties using vector technology. Currently, there is a distinct trend toward digital orthophotography (raster) because it is less expensive, and because it is more like a photograph — more understandable and readable by users.

Topology in digital mapping can be simply defined as the logical relationships between points (nodes); arcs (line strings which are properly connected vectors traveling from a defined node to another defined node, implying directionality with a defined polygon on the left and another on the right); and polygons themselves (defined by a polygon identifier point inside each polygon, and consisting of a closed series of arcs). For example, a fence corner could be a node, the fences between corners would be arcs, and if the fences joined back on one another without a gate, they would form a simple polygon. With a gate, the gate itself would be formed by two nodes and one arc, so the polygon would still exist, although more complex as it would consist of two different arc types.

GIS could not exist without topology. Incorrect edgematching between map sheets is currently a major problem on some projects, as this results in a breakdown of topology. Not all features may require topology; for instance, some users want continuous, topologically constructed contours, whereas others don't care if the contours are made up of separate disconnected lines.

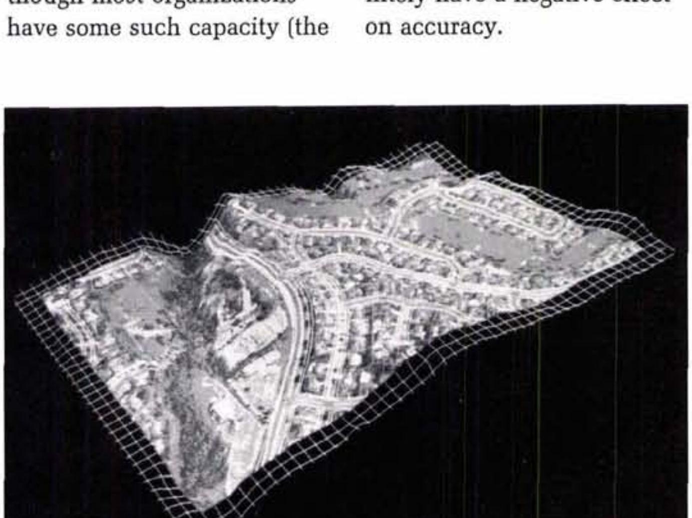
Current photogrammetric compilation procedures demand the digitizing of the various features (contours, roads, buildings, water bodies, etc.) as topologically correct arcs and polygons. Sophisticated clients will not accept non-closed polygons, dangles, overshoots, or vectors which are improperly coded. Another unacceptable condition is the crossing of contour lines in steep or obscured areas. Another problem is lines which are coincident but have different feature codes, e.g., a driveway ending may also be part of the edge of a road. In this case, the common line might have to be stored twice. These GIS requirements greatly increase the difficulty of creating and maintaining landbase maps.

The storage of vectors in 3-D greatly increases the difficulty (e.g. circular arcs in 2-D become spiral curves or ellipses, which are far more complex, in 3-D), editing (snapping lines in 3-D), and storage (50% more data) of digital vector landbases.

The author believes that in the future, ground elevations will be stored and manipulated less and less by contours, with more emphasis being placed on the storage of Digital Terrain Models (DTMs). Few mapping organizations presently use contour interpolation procedures for providing contours, although most organizations have some such capacity (the author's company has used this process exclusively since 1985).

The use of "soft" and "hard" breaklines combined with individual "mass points" is widely accepted as the best way of collection of DTM. In the author's opinion, the combination of the two types of breaklines should total at least 60% of the total of elevation points captured, the balance being strategically placed mass points. The final results are stored in a TIN (Triangular Irregular Network) file. Current point density for two foot contour mapping at 1″ = 100′ in an urban area should be around 30-50 points per acre.

One highly questionable procedure being used by some organizations is to hand-digitize the index contours and then use software to interpolate the intermediate contours. While this procedure could be useful in steep or obscured areas, it is unfortunately often used as a time-saver and will definitely have a negative effect on accuracy.



A wire mesh 3D digital terrain model overlaid with an orthophoto image.

Some organizations digitize their vectors directly into the graphics system (e.g. Kork, Intergraph, AutoCad) while others use batch processing (essential for contour interpolation) to create the vectors in their graphically correct form. Some organizations currently use highly elaborate proprietary software packages and modern, fast workstations to complete this process as efficiently as possible.

Graphics editing has replaced the old, tedious scribing process to produce the final map. When digital mapping was first done in the middle 1980s, graphics editing of the compiled vectors took 100% or more time, when compared with compilation time. Currently, modern processing software has cut graphics editing time dramatically. Modern tendency is to use computers to do what people used to do, freeing up the map makers to be more productive. However, graphics editing remains an essential component of photogrammetric mapping, but it is becoming more and more a Quality Control (QC) function as software becomes more powerful.

Hard copy mylar original maps are becoming less and less a requirement as the digital files become more used. Color electronic plotters at 400 dpi are currently used to produce hard copy maps which can be created at any scale of any required area, usually on paper, and, of course, in color. It is interesting to note that the need for perfect scale measurement on the mylar (non-stretch material) has almost entirely vanished, being replaced by the ability to measure distances or areas directly and far more accurately in the digital file.

Traditional maps remained in their original form and scale (on mylar or paper) forever. Modern maps are infinitely more versatile, being digital. They can be translated from their current form (perhaps AutoCad) into literally hundreds of different software environments. A few years ago (late 1980s) translation was a problem, but currently most leading mapping organizations have developed or purchased translators from one GIS software system to another. System integration of digital maps in complex multi-departmental organizations has certainly not been mastered at this time, and much remains to be done before many different users in different places can all access the maps efficiently.

In digital orthophotography, the size of the scanned pixel greatly affects the size of the files being created. At 25 microns (1,000 dpi) resolution, a 9″ x 9″ photograph holds 81 mb of data. The basic resolution of a high quality photograph is about 8 microns, so a full photograph at this resolution would hold about 800 mb of data which is for all practical purposes unmanageable, as of 1993. Not only individual photographs, but the orthophoto database at maximum resolution built for a large number of photographs, would become too large for practical purposes.

Clearly, the maximum resolution obtainable from modern photography is not practically useable at this time except for small portions of a few photographs. Current trends are to use scanning resolutions between 15 and 50 microns. Scanning a 1″=833′ (1:10,000) scale photograph at 15 microns results in a ground pixel size of 0.5 feet, which is a high enough standard of resolution for most mapping projects. 1:10,000 photography is currently being used on some major projects for 1″=100′ (1:1,200) mapping, easily meeting horizontal accuracy standards where the DTM is sufficiently accurate. When high precision scans are required, the use of flatbed transmissive scanners is desirable. Several are on the market, including the Zeiss PS-1 (7.5, 15, 30, 60, 120 microns) and the Vexcel 3000 (variable 8-180 microns).

The accuracy of the elevation data used during the ortho transformation from scanned image pixels to ground pixels has a very large influence on the accuracy of the final orthophotography. In the center of the photograph, even a large elevation error would have no effect on the orthophoto accuracy, whereas at a 45-degree angle an elevation error of 1 meter would result in a 1 meter horizontal error in the orthophoto. The error can be calculated from the formula: $e(o) = e(e) \cdot \tan A$ where e(o) is the resulting error in the orthophoto, e(e) is the error in elevation, and A is the viewing angle in degrees, outward from the center of the photograph.

NMAS accuracy standards for contours are fairly well defined (except for the spot elevation requirement which the author feels is unrealistic). The accuracy of DTMs is not clearly defined at this time by any national standards. It must be understood that a DTM of some sort is essential before a digital orthophoto can be produced. However, an accurate orthophoto can be produced with a far less detailed DTM than is required to produce contours. This is because the many minor breaklines required to portray contours in furrows and ditches, for example, are not necessary for the ortho generation. Conversely, an "ortho DTM" should not be used for contour interpolation.

One technique of flight planning alternatives which has been successfully used (e.g., the city of Riverside, California) is 60% sidelapped photography. Although this is more expensive because of nearly twice the number of photographs, the results are excellent because only the central portion of each photo is used for ortho-rectification, so there is far less outward radial displacement of building roofs and elevated bridges, and less radiometric variation across each image. Using 60% forward and sidelap, the resulting A.T. solution is extremely strong because each passpoint is measured on as many as nine different photographs.

Orthophotos have traditionally been created from photographs taken with the flightlines centered on the map sheets, enabling each map sheet to be exposed at a predetermined scale from a single photograph, thus obviating the need for splicing inside a sheet. However, in conventional orthophotography little consideration was ever given to image matching at the sheet edges. In a modern seamless GIS raster database, the sheet concept is becoming irrelevant because users will require maps at different scales and different areas, regardless of where the original sheets were designed. Mylars, which are of fixed scale and area, will become less important in the future and are not a requirement on several current large digital orthophoto projects.

Making a digital orthophoto is not a very difficult process. There are currently as many as twenty systems available commercially, some even running on PCs. The difficult part is managing the data, particularly on a large project. For commercial production, large computing resources are needed for file handling and storage, and very close attention must be paid to system integration and management. When each orthophoto may require processing of 100 mb of data six or seven times during the process, and ten or more orthos must be made every day, plenty of computer power and good data management are essential.

Storage of a large raster database in a format allowing fast access by multiple users at any required resolution is a real challenge. Different approaches are being used in the federal government where each quad or quarter-quad sheet will be stored at single resolution in a separate file, whereas in the private sector the whole mapped area is stored at multiple resolutions as a seamless database, regardless of any sheet locations. There are pros and cons to each approach.

Softcopy photogrammetry could be defined as using raster digital data as opposed to using film or paper. A hardcopy stereoplotter uses traditional film diapositives for viewing, where a softcopy workstation will use a raster file, scanned from each diapositive. Although digital orthophotography is softcopy photogrammetry in a sense, this section is limited to the stereo viewing of raster images similar to traditional viewing in a stereoplotter.

Only a few workstation systems (including the Intergraph Image Station and the Helava DPW) are currently used in a practical way. Both have only recently been made available to the commercial market, having been developed originally using Department of Defense funding of military projects. In the author's opinion, no system currently used has progressed to the stage where it can match the accuracy, efficiency, and productivity of a conventional analytical plotter. This is because of the complexities of the software and the problems in handling of the huge raster files needed for every single photograph. The fact that a hardcopy diapositive has a resolving power of less than ten microns is inescapable, and raster files at that resolution are far too large for the current state of the art to use efficiently, day in and day out.

Consider the tasks involved in performing a relative and absolute orientation in a softcopy system, a task which takes less than fifteen minutes on a conventional analytical plotter:

- Scanning of the two diapositives (low resolution 56 mb, high resolution 300 mb, each!)
- Transfer the files to the workstation in the correct format
- Measure the raster coordinates of the fiducial marks
- Resample both files to make the raster parallel to the epipolar line
- Observe both files in stereo, and complete the relative and absolute orientations

Clearly, there are some very significant processing and file handling tasks here, and a lot of systems management expertise is a real requirement. Only then can any exploitation of the stereo model be performed by direct digitizing of vectors on top of the raster image. One great advantage of softcopy will be the stereo superimposition of the vectors in 3-D on top of the raster 3-D image. In this way, the accuracy of contours or other elevation data can be readily checked.

The accuracy of softcopy photogrammetry is limited by the pixel size used. Software is being developed that can result in sub-pixel accuracy, but in general the accuracy of a softcopy workstation will not exceed that of traditional analytical plotters in the foreseeable future except where automatic correlation can be used in very specific instances.

When discussing Geographic Information Systems, it is important to remember that the photogrammetric phase builds the foundation of the GIS. Later, the main layers will consist of information such as cadastral, street centerlines and addresses, utilities, soils, political boundaries and the like all of which have much more difficult topology than the photogrammetric base.

Photogrammetry has emerged from being the mainstay of map-making techniques, mostly in small companies, to the premier tool for building landbases for GIS. This, of course, means an almost totally digital environment, and the handling of vectors in a large GIS became practical only in the mid-1980s. At first, map makers merely tried to reproduce manual maps in a digital representation; later, more emphasis was placed on "clean" graphics where the lines are perfectly connected and topologically constructed. It was difficult for map makers to improve quality and still keep costs down, and only a large investment in sophisticated software and hardware, with ever-faster computers, has made this possible.

In vector GIS landbases, there is a distinct tendency toward simpler, less comprehensive capture of detail, because of the expense of capturing vectors, one point at a time. In the author's opinion, the most important vectors are road edges, derived road centerlines, railroads, and major water feature lines.

The advent of digital raster technology in the commercial arena around 1989 opened up an avenue which, in the author's opinion, will become the standard landbase of the GIS industry, because:

- modern computers can handle the massive amounts of data
- it is much less expensive than vector landbases
- it is just as accurate (if not more so) than vectors, provided that the DTM is sufficiently accurate
- being a photographic image, more detail is visible and interpretable than a vector landbase which is often limited in content

Revision of photogrammetric maps has always been an ordeal costing far more in time and effort than most users would expect. In the modern digital environment, the challenges are equally large.

Superimposition of the vectors on top of the stereo image in a stereoplotter has been possible for some years, but the hardware and software requirements have made it expensive, and its usefulness and cost effectiveness for original map compilation is debatable. However, for map updating or revision, superimposition is essential as it affords the best means of viewing the old map superimposed upon the new photography, giving the technician a powerful tool in seeing what changes need to be made.

The original data may have been translated from the photogrammetrist's original files to the final user's particular GIS software environment. What is more, the files may have subsequently been modified by the user. Therefore, the user's files must be translated back to the photogrammetrist's files, updated, and then re-translated to the user's system. This is more difficult than it sounds, particularly when considering that data compiled four or five years ago may have been compiled to less strict standards than apply today.

What about the future?

Raster image correlation is an extremely fascinating field of development sponsored mainly by military projects and the availability of sátellite photography (which, of course, is raster imagery, though different in geometry from scanned photographs taken with conventional aerial cameras). Raster correlation is performed by the computer recognizing the raster patterns of objects (bushes, corners of buildings, road intersections, and the like) on both images of an overlapping pair of photographs. As it is performing this process, the locations and elevations of correlated objects can be recorded and stored; if enough objects are correlated, both the DTM and the raster orthophoto can be developed at the same time. The technology has tremendous potential, but the photogrammetrist should remember that it works well using small scale imagery where ground obscurity caused by vegetation and man-made structures is of little importance. Currently, it doesn't work well in large scale imagery, and probably will not for some time to come, as too much manual editing is required in obscured areas.

Another exciting development is the use of raster files and image correlation in aerial triangulation. Within the next few years, we will be able to omit the pugging stage in A.T. and allow the computer to automatically locate passpoints in adjacent photographs and flightlines and proceed directly with the final bundle adjustment. Instead of having a pugged diapositive of the A.T. photography, we will have stored patches of imagery with the passpoints automatically identified. Also, an approximate, if not final, absolute orientation can be made immediately from the bundle adjustment parameters.

Automatic recognition of objects (such as tanks on a battlefield) has for some years been the objective of researchers. Patterns consist of all sorts of objects and combinations of lines, both straight and curved. Much progress will certainly be made in this field in the future, particularly when using satellites or high-flown photography. However, in large scale photogrammetric mapping, completely automatic pattern (feature) recognition will not be feasible or practical for many years, or at least until computers and software become as smart as the human brain of a photogrammetric operator who spends much of his or her time interpreting patterns on the ground which are not clearly discernible due to obscured terrain.

At some time in the future we will use data from purely digital cameras in softcopy workstations instead of film from conventional cameras in hardcopy analytical plotters. Possibly, and certainly hopefully, these cameras will have the capability of using radar which can enable operation at night, or in cloudy conditions. That would really be a breakthrough! However, many problems remain to be solved, two in particular: firstly, the geometry of data which are not simultaneously collected (like satellite data where each row of pixels is exposed separately at different time intervals; secondly, the error-free storage of the vast amounts of data required to faithfully replace all the information (about 800 mb) which a single photograph captures today on about ten inches of film.

What is the future of conventional hardcopy photogrammetry? It will certainly survive in small companies performing small mapping projects, for many years. However, the power of modern computers and the ingenuity of scientists is quickly changing the course of photogrammetry. There will be a change of focus from expensive stereoplotters to ever-cheaper software, and this will have a profound effect on the vendors of the photogrammetric equipment which has served us so well, for so long.

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