

Developments in digital photogrammetric systems for topographic mapping applications

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ABSTRACT

This article sets out the current situation regarding the development of digital photogrammetric systems (DPS) as applied to the field of topographic mapping. It describes the devices used for input to and output from such a system, as well as its main element, the digital photogrammetric workstation (DPW). The various sources of digital image data and the volumes of such data that have to be handled are first dealt with in some detail. Then follows a review of the photogrammetric quality scanners currently available on the market. Next, the hardware aspects of the DPW are described, including processors and data display, stereo-viewing and measuring/positioning devices. A classification of DPWs is then given, accompanied by a table setting out the main characteristics of those systems commercially available at the present time. The article then goes on to describe the algorithmic and software aspects of DPWs, including the software modules developed for orientation, triangulation, map compilation, DEM generation and ortho-image production. The final section deals with the output side of the DPS, and includes a review of the various types of plotter that are available to generate hard-copy maps and ortho-images from the digital data produced by DPWs.

The last 10 or 12 years have seen the steady development of digital photogrammetric systems (DPS): from the individual pioneering systems devised by research groups in certain European universities and the specialized systems produced for military intelligence and mapping agencies in the United States, to the first commercially marketed digital photogrammetric workstation (DPW) (the Kern DSP1, shown at the 16th ISPRS congress in Kyoto in 1988), and gathering momentum with the advent of a wide range of systems with ever-greater capabilities from a variety of suppliers. This development first became apparent at the 17th ISPRS congress held in Washington in 1992. Since then, in the four years leading up to the 18th ISPRS congress in Vienna in 1996, the pace of development has increased still further [20]. While the system suppliers have been very aggressive in promoting the new technology and numerous papers have been published in the technical and scientific press on every possible aspect, only since 1994 have the systems been sold in any great numbers. In Europe, a few, mainly government, mapping organizations such as the Ordnance Survey of Ireland [15, 10], the Institut Cartografic de Catalunya [3] and Lantmäteriverket in Sweden [8] have embraced the new technology in a fairly comprehensive fashion, albeit to supplement a still considerable analytical plotter capacity. More commonly, however, national mapping agencies and commercial survey companies have invested more cautiously in one or two systems, with a view to assessing the new technology and gaining experience before increasing their commitment (eg, the Canada Centre for Topographic

Information [1]). Undoubtedly, the greatest success till now of the DPS has been in the field of digital orthophotograph production and in the closely associated area of digital elevation data acquisition.

In the meantime, the existing range of analytical plotters using hard-copy photographs has continued to sell extremely well, especially where the emphasis is on traditional stereo-compilation based on feature extraction from aerial photographs. In this respect, the well-established Leica SD2000/3000 and Zeiss Planicomp P3/P33 series remain the market leaders. On the other hand, actual new developments in analytical photogrammetric instrumentation have dropped off quite noticeably. Indeed, since the author [18] reviewed the field in detail in 1992, the only new analytical plotters to appear have been the Adam Technology Promap from Australia, the Cartographic Engineering CP2 from the United Kingdom and the Stereoanagraph-6 from the new Ukrainian supplier, GeoSystem. However, there still seems to be considerable activity in converting analog stereoplotters to their analytical plotter equivalents, eg, by using the conversion kits offered by Qasco and Adam Technology. There is also further quite similar activity in upgrading older analytical instruments such as the Wild BC, Kern DSR and Zeiss C100 series, and the Intergraph IMA to run under PCs instead of the original desktop computers or workstations that they were supplied with. Conversion kits for this purpose are available from DAT/EM, ABC Software Developers, Leica, etc.

When comparing the two technologies, the great advantage of the DPW is that it eliminates all the expensive high-precision mechanical components of the analytical plotter, such as the photo stages, carriages, lead screws, etc, as well as the associated measuring components such as linear or rotary encoders. Nor are most of the high-quality optical components of the analytical plotter required—although many of the higher-bracket DPWs feature stereo-viewing systems that are quite costly items to incorporate. Indeed, the more sophisticated and capable DPWs based on high-performance graphics workstations are still quite expensive—at present they cost more than the corresponding analytical plotter, but prices should fall in the future. Moreover, as with analytical photogrammetric instrumentation, there are less capable but much less expensive DPWs available that can satisfy the needs of many less demanding users.

BASIC ELEMENTS OF DIGITAL PHOTOGRAMMETRIC SYSTEMS (DPS)

The main characteristics of a DPS (Figure 1) are as follows:

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(1) It is a system combining computer hardware and software that allows photogrammetric operations to be carried out on digital image data.

(2) These operations are carried out on sets of image data consisting of picture elements (pixels) of fixed shapes and sizes. Each individual pixel is assigned a brightness value (BV), which gives the value of the radiance from the object field falling on each individual element of the imaging sensor.

(3) The imaging sensor can take the form of:

- a digital camera equipped with an areal array of charged coupled detectors (CCDs)
- a pushbroom scanner featuring a linear array of CCDs.

Each of these detectors gives a direct output of the image data in digital form through analog-to-digital (A/D) conversion of the radiance value, which is measured electrically for each individual element of the sensor.

(4) For topographic mapping operations, however, digital image data are most often derived from the frame images on photographic film produced by an aerial camera. These film images need to be converted to digital form by using high-precision scanners equipped with linear or areal CCD arrays. In this case, the scanner forms a vital and integral part of the DPS.

(5) The main element of a DPS is the DPW, on which the required analytical (*ie*, numerically- and mathematically-based) photogrammetric operations are carried out to produce data for input to:

- digital mapping systems
- CAD systems
- GIS/LIS systems.

(6) These photogrammetric operations include:

- manual (operator-controlled) operations such as the feature extraction involved in map compilation and revision
- automatic or semi-automatic operations such as the generation of digital elevation model (DEM) data and ortho-image data.

(7) Final output may take the form of:

- vector line maps
- digital terrain model (DTM) data
- digital ortho-images.

Here, in addition to devices that can record purely digital data, the overall DPS will include devices such as raster-based plotters and film writers, which can produce hard-copy maps, perspective views of the terrain surface and continuous-tone images from the DPW image data. Essentially, these carry out a digital-to-analog (D/A) operation.

In view of these specific characteristics, this article will review developments in the four main elements of a DPS:

- the acquisition of digital image data from different imaging sensors
- the scanner technologies involved in digitizing photographic images
- the DPW itself
- the main output devices

(as used in the field of topographic mapping).

Non-topographic applications will not be dealt with here.

IMAGE DATA ACQUISITION AND INPUT TO A DPS

There is a vast range in the volumes of digital image data that come from different sensors and have to be handled and stored in a DPS. In the case of digital cameras, the data volumes are relatively small. Few such cameras are used from aircraft; they are encountered mainly in close-range photogrammetric applications. A typical video or CCD areal array camera generating black-and-white (grey-level) images will have an image area of 512 x 512 pixels = 262,144 pixels (0.25 megapixels), requiring 0.25 Mb of storage (where the data for one pixel require 1 byte of storage). Higher-resolution cameras of 1000 x 1000 and (as yet still uncommon) 2000 x 2000 pixels would generate 1 Mb of data and 4 megapixels (requiring 4 Mb of storage), respectively. IGN in France is reported to be testing an experimental airborne digital camera with a 2000 x 3000 pixel format; this will produce 6 Mb of data per frame.

Considering next the pushbroom scanners commonly used in remote sensing and photogrammetric operations conducted from satellites, the data volumes are considerably larger. Thus, for example, the Spot HRV pan sensor produces a single grey-level image with 6000 x 6000 pixels = 36 megapixels, requiring 36 Mb of storage; whereas the Spot XS imager generates 3000 x 3000 pixels, giving a 9-megapixel image per spectral channel and requiring 27 Mb of storage for a three-channel false-colour image or scene.

Coming finally to the standard aerial photogrammetric camera with its 23 x 23 cm format, the resolution on the original negative film will lie in the range 20 to 40 line pairs per mm (lp/mm) for low contrast targets (1.6:1 contrast ratio). Because theoretical and practical considerations indicate that two pixels are needed to represent one line pair [22], this equates to pixel sizes between 25 and 12.5 μm (Figure 2). The latest high-performance cameras equipped with forward-motion compensation (fmc), gyro-controlled stabilized mounts and high-resolution film (such as the Wild RC30 or the Zeiss RMK-TOP) give 60 lp/mm, which is equivalent to a pixel size of 8.5 μm . Therefore, photogrammetric quality scanners which convert the film image to digital form must provide a minimum pixel size of 8 to 10 μm if the resolution inherent in the negative film is to be preserved.

Regarding data volumes, if the monochrome film resulting from the use of an aerial camera is digitized at a pixel size of 25 μm (*ie*, 1000 dots per inch (dpi)), equivalent to 20 lp/mm, this would give rise to 9200 x 9200 pixels = 85 megapixels (85 Mb). With a 15 μm sampling interval, the data volume increases to 235 megapixels, whereas with a 10 μm pixel (*ie*, 2500 dpi) the data volume increases to 529 megapixels (or 529

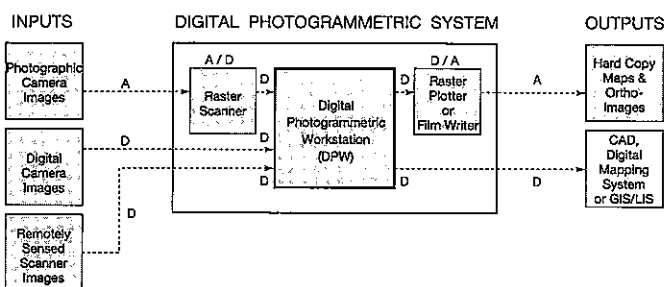


FIGURE 1 Overall concept of the digital photogrammetric system (DPS)

Mb) per image (Figure 2). The use of colour or false-colour photography instead of monochrome triples these figures for data volumes.

Because most photogrammetric operations involve the use of stereo images, a pair of standard aerial photographs will generate in excess of 1 gigabyte (1 Gb) of data at the 10 μm pixel level, equating to a resolution of 50 lp/mm. The resulting data volumes needing to be stored and handled by the DPS are daunting to say the least. Therefore, image compression/decompression techniques such as JPEG are used to alleviate some of the problems associated with these large data volumes. Even then, the use of RAID technology with capacities of 50 to 100 Gb is not uncommon in those mapping agencies that have adopted DPS.

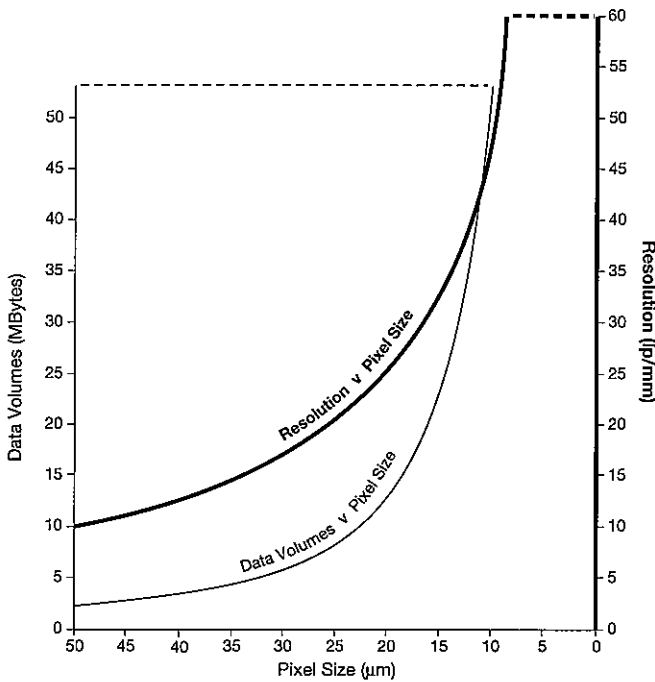


FIGURE 2 Resolution and data volumes resulting from scanner pixel size

SCANNERS

As noted above, high-precision digitization of the hard-copy photographic images generated by metric cameras is currently an essential component of an operational DPS, and will remain so until a comparable high-performance digital camera is developed and adopted by the mapping community. This digitization is provided by scanners, which normally use one of the four main technologies (Figure 3) currently available for use with stable transparent film images, *ie*:

(1) A rotating drum scanner equipped with a scan head. This has been used by the Optronics, Hell, Crosfield and Howtech film digitizers employed extensively in the graphic arts world. Some of these drum film scanners can meet the requirements regarding minimum pixel size, geometric accuracy and radiometric range needed to digitize aerial photographs for photogrammetric purposes; others cannot.

(2) A 2D flatbed scanner equipped with a photo head or CCD linear array, which scans the photograph in a raster pattern, giving a series of parallel swaths. This is

quite commonly used in purpose-built photogrammetric scanners, most notably the Zeiss/Intergraph series but also the Wehrli RasterMaster and the ISM DiSC.

(3) A 1D scanning linear array of CCDs, which scans the photo in a single sweep. This is used only by the XL Vision OrthoVision 950.

(4) A CCD areal array (often described as a CCD camera or staring array), which allows patch-by-patch scanning of the photographic image with reassembly of the patches later into a single seamless image. This is used in the Leica/Helava DSW series and in the Vexcel, Lenzar, Rollei and Topcon scanners.

High scanner accuracy is obligatory if the introduction of errors into the geometry of the photographic image is to be avoided. The photogrammetric requirements of these scanners therefore call for linear measuring resolutions of 1 to 2 μm and accuracies (rmse) of ± 3 to 5 μm on each axis, together with minimum pixel sizes of 8 to 10 μm (2500 dpi). In other words, the same accuracy requirements apply as for a monocomparator or a mainstream analytical plotter. Only with such rigorous specifications can any mismatches (gaps or slivers) between the swaths or patches used in many scanners be avoided. Using a powerful PC or graphics workstation equipped with sophisticated software to carry out the necessary control and storage functions, the time typically taken to scan a single black-and-white (monochromatic) photograph lies in the range 5 to 20 minutes for a 23 x 23 cm image at pixel sizes of 10 to 15 μm . These functions often include the automatic measurement of the fiducial marks for inner orientation, using image matching techniques.

On the radiometric side, the digital image data are normally produced in an 8-bit form, providing 256 levels in terms of grey scale. However, some recent scanners offer 10 bits (1024 levels) in terms of their internal digitization, although the output data may still be delivered to users in 8-bit form. For colour photography, the standard output is in 24-bit (3 x 8-bit) form, using, for example, a motorized RGB colour wheel (Wehrli RasterMaster, Vexcel, etc) or a tri-linear CCD arrange-

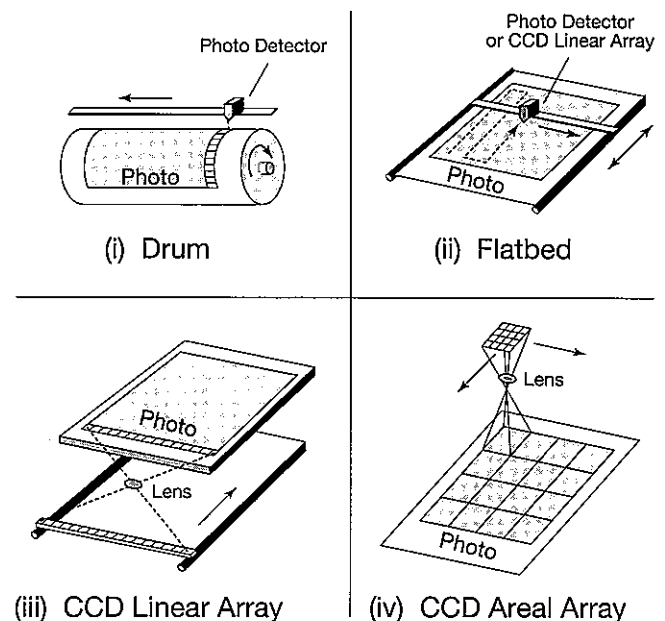


FIGURE 3 Principal scanner technologies

ment (Zeiss/Intergraph SCAI/TD scanner) to ensure the required colour separation of the image.

Because most earlier scanners were designed for use only with positive film transparencies (diapositives), considerable time and expense were incurred in making film diapositives from the original negative roll film before scanning could take place. This is a serious matter if a large number of photographic frames have been acquired for a mapping project. Thus a demand has arisen from some users for the scanning/digitizing operation to be carried out using the original negative roll film. This brings its own problems. The production of the individual diapositive did allow electronic dodging of the image to improve its contrast and interpretability. Therefore, scanners that can handle negative roll film (eg, the Leica/Helava DSW 300) must be provided with software to carry out sophisticated filtering, using suitable enhancement algorithms to emulate the dodging process.

There are already a large number of photogrammetric quality scanners on the market (see Table 1). The Zeiss/Intergraph series can be taken as representative of the type (2) scanners. The PS1 uses many of the mechanical components (ways, encoders, etc) of the Planicomp P3 analytical plotter. Scanning takes place through the precision movement of the photo carriage on which the transparency is mounted, in a series of parallel raster scans or swaths under the stationary light source, optics and CCD linear array of detectors (Figure 4). The newer SCAI (Zeiss) or TD (Intergraph) models, driven by Silicon Graphics and PC workstations, respectively, have a larger range of pixel sizes and an improved grey-level range. Compared with the earlier PS1 series, however, the principal change lies in their capability to handle negative roll film. This requires additional motors and encoders to sense and control the spools on which the negative roll film is wound, together with more sophisticated electronics and software to

control their movement—including the search for specific frames. Also the light source, optics and CCD linear array now move as a unit against the fixed position of the film on a register glass.

The Vexcel VX3000 can be taken as representative of the type (4) scanners, although its 25 x 50 cm format, designed to accommodate the large-format (23 x 46 cm) cameras used by U.S. military mapping and reconnaissance agencies, is exceptional. First, a precision grid or reseau [11] is scanned and the coordinate positions are determined. Then with reference to this grid, a CCD areal array camera is driven over the photograph, scanning the image in a series of patches or tiles. The final stage is transforming the individual tiles into a seamless pixel array (Figure 5), using the known reseau positions.

It is interesting to note that, with the relatively few DPWs in many mapping organizations and the relatively high cost of photogrammetric quality scanners, a number of scanning bureaus have been established in various countries. These offer scanning services even to their competitors in the commercial mapping field, because this helps them recover some of the purchase/operation costs of these high-performance devices.

There are of course numerous lower-cost scanners capable of converting hard-copy prints into digital

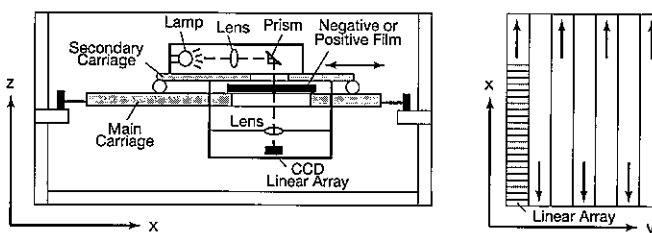


FIGURE 4 2D flatbed scanner equipped with a CCD linear array

TABLE 1 Digital photogrammetric scanners

	<i>Geosystem Delta Scan</i>	<i>ISM DiSC</i>	<i>Leica Helava DSW 100</i>	<i>Leica Helava DSW 200</i>	<i>Leica Helava DSW 300</i>	<i>Lenzpro 2000/2001</i>	<i>Rollei- Metric RS</i>
Scan area (cm)	30x30	25x25	25x25	26.5x26.5	27x27	30x30	22x22
Linear res (µm)	1	1	1	1	0.5	0.25	1
Accuracy (µm)	±3	±5	±3	±3	±2	<1	?
Pixel size (µm)	14	9x9	8 to 75	9 to 15	5 to 16	3 to 254	12x18
Grey levels	256	1024	256	256	1024	256/1024	16 of 256
CCD sensor	2048x1	8000x1	1270x1270	2029x2044	2029x2044	Patch	2048x1
Roll film	No	Yes	No	?	Yes	Yes	No
Computer	PC	PC	Sun/PC	Sun	Sun	SGI/Sun	?
	<i>Topcon PS 1000</i>	<i>Vexcel VX 3000</i>	<i>Wehrli Raster- Master RM1</i>	<i>XL Ortho Vision</i>	<i>Zeiss/ Intergraph PS-1</i>	<i>Zeiss/ Intergraph SCAI/TD</i>	
Scan area (cm)	24x24	25.4x50.8	24.5x24.5	23x23	26x26	25x27.5	
Linear res (µm)	1	1	0.5	1	1	1	
Accuracy (µm)	3	3	±4	±3	±3	±3	
Pixel size (µm)	11.5x13.5	8.5 to 160	12 to 96	9 to 73	7.5 to 120	7 to 224	
Grey levels	?	256	256	256	256	1024	
CCD sensor	280x488	512x512	2048x1	24,000x1	2048x1	5632x1	
Roll film	No	Yes	No	Yes	No	Yes	
Computer	PC	SGI/Sun	PC	PC	Interpro	SGI/PC	

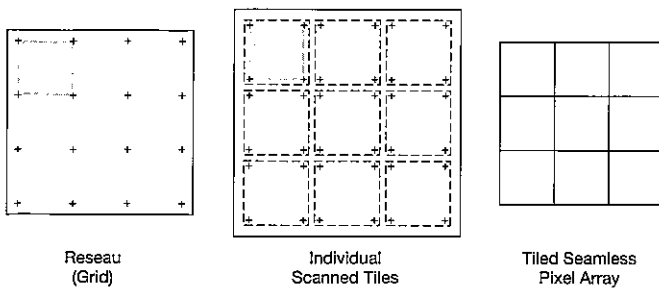


FIGURE 5 Use of a CCD areal array with patch-by-patch scanning and transformation of the tiles or patches into a single seamless pixel array

images. These have been developed for use mainly in the desktop publishing industry, with scanning resolutions in the range 300 to 600 dpi (80 to 40 μm resolution). This leads to the generation of data with a much larger minimum pixel size than that compatible with the resolution of the aerial photograph. From the photogrammetric point of view, however, they have various other limitations besides the lower resolution and larger pixel size, including:

- a restricted 4- or 6-bit grey-level range
- they are often designed to accept prints only and cannot handle film transparencies
- they are often built to accommodate the standard A4 page format (21 x 25 cm) and thus cannot accommodate standard 23 x 23 cm format aerial photographs (which need to be digitized in two separate operations)
- their geometric accuracy. Positional errors (rmse) of ± 2.4 pixels have been reported even at the rather crude scanning resolution of 80 μm pixel (300 dpi). Data produced with such a device cannot normally be used for serious photogrammetric work, although this might be possible if it could be calibrated in an appropriate manner and had an appropriate format size.

DIGITAL PHOTOGRAMMETRIC WORKSTATIONS (DPWs)

The DPW forms the core of the DPS, and consists of a graphics workstation with enhanced image processing, memory and display capabilities (including in most but not all cases a stereo-viewing facility), and the appropriate software to support photogrammetric operations [6, 20].

HARDWARE ASPECTS OF THE DPW

The main features of DPW hardware (Figure 6) are as follows:

- (1) A powerful processor (CPU) and a very large memory (RAM) are required to handle the large volumes of image data that are an inherent feature of a DPS.
- (2) Additional processing capability can be provided to ensure the timely execution of computationally intensive tasks, eg, automatic image matching for measuring DEM data. This additional capacity can be provided by:
 - a graphics accelerator
 - a digital signal processing (DSP) board
 - an array processor.
- (3) Considerable data storage is needed: high-capacity hard disks and back-up storage devices (in the multi-gigabyte range) are required to store the image data

being used in a DPS.

(4) Very fast data transfer is required between the RAM, the video memory driving the image display and the main data storage on hard disk.

(5) A very high resolution colour display monitor with a stereo-viewing capability is required.

(6) A 3D measuring device to allow the precise positioning of a measuring mark (cursor) for height measurement is a necessity for manual (operator-controlled) mensuration tasks, such as identifying and measuring ground control points; feature extraction for map compilation; and for data editing.

COMPUTER HARDWARE ASPECTS

With regard to processors (CPUs), the Unix-based graphics workstations that form the basis of those DPWs at the top of the performance scale use RISC (reduced instruction set computer) processors almost exclusively. The two most common types by far are the Sparc processors used in the Sun SparcStation and Ultra workstations, and the MIPS processors used in the Silicon Graphics (SGI) Indy and Indigo workstations. These two brands of workstation are used by the traditional mainstream photogrammetric system suppliers (eg, Leica/Helava (both Sun and SGI); Zeiss and Autometric (SGI); and Matra (Sun)). To date, the comparable alternative RISC processors from DEC (Alpha) and Hewlett Packard (PA) have not been adopted for use in DPWs to any substantial extent—although Leica/Helava have delivered a few of their DPW 770s with Hewlett Packard workstations. Intergraph has used its own proprietary Clipper RISC technology in the Interpro workstations that form the basis of its InterMap Digital (IMD) DPWs [9].

Increasingly, however, there has been a trend for DPWs to use PCs equipped with Intel processors. The software for some of the earliest PC-based DPWs (eg, the R-WEL DMS, the Topcon PI-1000 and the DVP) was written for the MS-DOS operating system, and used quite modest amounts of RAM (640 Kb or 1 Mb) and Intel 286 or 386 processors. Relatively modest hardware

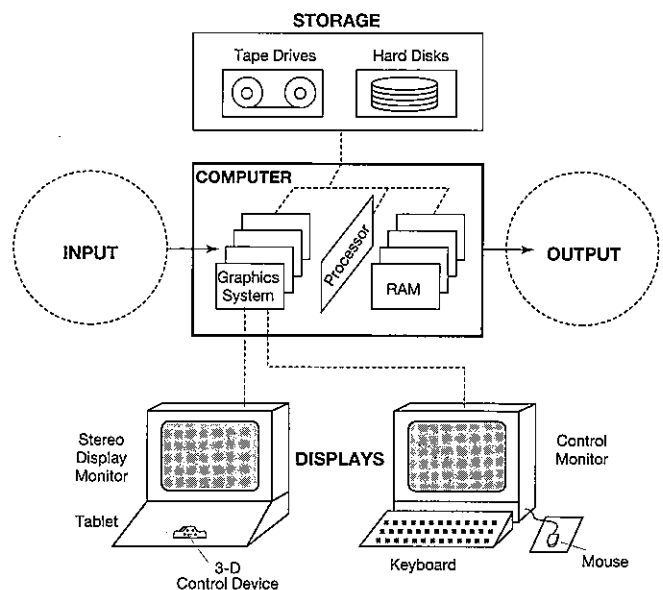


FIGURE 6 The main hardware elements of a digital photogrammetric workstation (DPW)

requirements are also a feature of some of the more recently developed DPWs, such as the KLT Atlas/DSP and the Galileo Stereodigit and Microdigit, which are still based on MS-DOS. In their current forms, all these various MS-DOS-based DPWs will run satisfactorily using Intel 486 processors and a minimum of 8 Mb of RAM—although they will of course perform more quickly on PCs with Pentium processors. At the other end of the PC scale are the newly developed DPWs from ISM (DiAP), Intergraph (Image Station Z), Leica and PCI (both SO CET SET) and DAT/EM (Summit PC), all of which run under the Windows NT operating system and use high-specification PCs equipped with twin Intel Pentium processors.

As far as memory is concerned, on the Unix-based and Windows NT-based DPWs—all of which use graphical user interfaces (GUIs)—32 Mb of RAM is the minimum, 64 Mb is common and 128 Mb is by no means uncommon! As noted above, there is also a need for the DPW to store the large amounts of data associated with digital images. This is achieved by using hard disks of multi-gigabyte capacity, which are capable of high transfer rates to and from the RAM. Usually, these are supplemented by CD-ROM drives, which may be of the multiple platter type and can handle CDs containing image data (from data suppliers) and system software (from DPW suppliers). The back-up and archiving of data is normally carried out using compact tape drives with DAT or Exabyte data cartridges.

Graphics accelerators have a special place in DPWs—principally to assist in implementing stereo-viewing, with its need for rapid refresh rates, especially in those systems using alternating imaging on the display screen. They also assist with image roaming over the stereo model. Thus the Leica/Helava and Intergraph DPWs have both used VITec graphics processors for these purposes, whereas the latest Intergraph TDZ workstation with dual or quad Pentium Pro processors features Intergraph's own GLZ graphics accelerator. All these special accelerator boards incorporate their own video memory (VRAM) to store the images needed for display, and to implement panning, scrolling and zooming operations in a practical manner. Although many early prototype DPWs built by university groups featured digital signal processors or array processors to speed up computationally intensive tasks (eg, the image matching operations used in stereo-correlation for DEM production), they have not been a feature of current offerings from the commercial system suppliers. However, the original model of the Matra Traster T10 DPW did incorporate an array processor, as did the I²S PRI²SM—which seems to have disappeared from the market recently.

DATA DISPLAY AND MEASUREMENT

Using a high-resolution display monitor is obligatory with a DPW, with 1024 x 1024 pixels = 1 megapixel being the minimum resolution to display image data on the screen. When displaying an image with 10 μ m pixel size at full resolution on such a monitor, it should be realized that an area of only 1 x 1 cm from a standard 23 x 23 cm format aerial photograph is displayed. The use of a 2-megapixel, 27-inch (68.5 cm) wide display monitor by Intergraph [9] was quite exceptional; to date, this has not been adopted by other system suppliers.

Recently, however, Intergraph itself has exceeded this by adopting the 28-inch (71.1 cm) 2.5-megapixel InterVue screen based on HDTV technology for use on its new Image Station Z DPW. Associated with the requirement for high resolution is the need for high refresh rates of the monitor screen (typically 100 or 120 Hz), especially if the left and right images needed for stereo-viewing have to be alternated on the screen at 50 to 60 Hz to obviate flickering in the stereo model. Currently, only a limited range of such high-frequency monitors are available on the market. Many DPWs are supplied with two monitors, one for displaying the image, the other for displaying system information, commands, prompts, etc, using menus and dialog boxes in conjunction with a GUI.

The operator moves the cursor (a cluster of pixels forming a cross or circle) around the image, using a control device, such as a mouse, trackball, digitizing tablet or handwheels, to apply the required screen pixel increments. The necessary movements can be implemented by using:

- a fixed cursor with a moving image (as used in analog and analytical stereoplotters)
- a fixed image with a moving cursor.

The second option is much easier to implement. In the first option, the continuous movement of the image and its graphics overlay against a fixed cursor is a computationally/memory intensive operation. Subpixel movement of the cursor is obtained by magnifying (*ie*, zooming) the image but not the cursor.

STEREO-VIEWING

This facility is regarded by most photogrammetrists as an absolute necessity, for both measuring the ground control points needed for absolute orientation and subsequently measuring the detail (now called feature extraction!) required for topographic map compilation and the 3D digital data needed for use in a GIS/LIS environment [19]. It is also a vital element in carrying out map revision and editing the digital elevation data produced by automatic image matching techniques. Last but not least, it also permits the stereo-superimposition of vector data on the stereo model for accuracy checks and completeness. Thus virtually all DPWs feature stereo-viewing and measuring capabilities—except for one or two systems from companies that specialize primarily in the remote sensing field and appear to be less aware of the attributes of stereo-viewing.

Five methods are currently in use, although others are possible (see [16]).

(1) The first method is to use two flat-screen monitors, displaying the left and right images of the stereo pair, respectively. These can be viewed using a mirror stereoscope or a more complex optical train (Figure 7). Alternatively, the two monitors can be set at right angles to each other, one with its axis pointing horizontally, the other pointing vertically upwards. One has a horizontal polarization sheet placed in front of it, the other a vertical polarization sheet. A large semi-reflecting mirror set between the two monitors acts as a beam splitter and allows the two component images to be superimposed on each other. The operator wears appropriate spectacles with horizontally and vertically polarizing filters to allow stereo-viewing (Figure 8). This arrangement was used by Matra in its Traster analytical plotters for hard-

copy photographs. Now the same basic arrangement is being used with DPWs, *eg*, on the Topcon PI-1000 and on the recently introduced Galileo/Siscam Stereodigit and Microdigit DPWs [2]. In each case, quite small monitors are used for the image displays, which rather limits their resolution; on the other hand, there is no dynamic alternating imaging with the risk of flickering. The Microdigit uses twin liquid crystal displays; all the other DPWs in this group, however, use conventional CRT-based monitors.

(2) An alternative approach is to display the left and right images side by side on a single monitor and view these through a simple mirror stereoscope—the so-called split-screen stereo method (Figure 9). This was the method used in the Kern DSP1, and it is currently used in the DVP marketed by Leica [5], as well as in Leica's own 600 series DPWs. GeoSystems' Delta workstation is another DPW using this arrangement [13].

(3) A low-cost solution is simply to superimpose the two component images of the stereo pair on the screen of a single colour monitor, with one image displayed in red and the other in green, using the anaglyphic technique familiar to photogrammetrists from early analog

stereoplotting instruments based on optical projection, such as the Multiplex, Balplex, Kelsh Plotter, etc. Users wearing spectacles with the corresponding red/green filters view the resulting stereo model on the monitor (Figure 10). This method is used in the R-WEL DMS system [21] and in some systems, such as TNT-MIPS, originating from remote sensing system suppliers. Obviously, use is limited to monochrome (black-and-white) images.

(4) A commonly used stereo-viewing system on DPWs alternates the left and right component images on a single monitor screen at high speed (*eg*, 50 to 60 Hz per image). Viewing is carried out using spectacles equipped with alternating shutters synchronized with the alternating images on the monitor (the left eye sees only the left image and the right eye sees only the right image) (Figure 11). Again, the basic idea is familiar to photogrammetrists who have used systems such as the stereo-image alternator (SIA) on older optical projection instruments (*eg*, the Balplex and Kelsh plotters). These used mechanical shutters, however; those for DPWs use electronic PZLT or LCD alternating shutters that are synchronized with the display image, either by direct

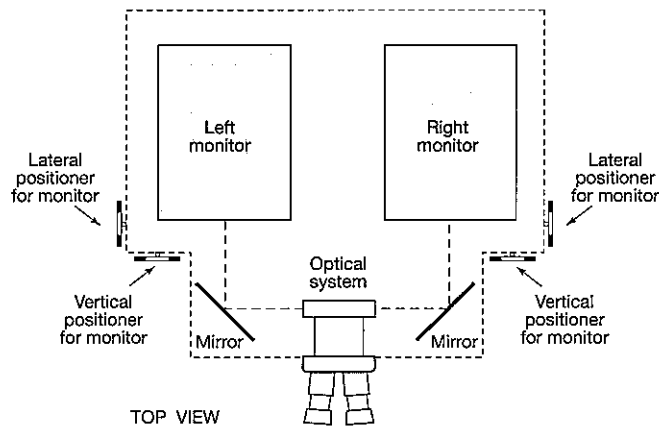


FIGURE 7 Twin monitors viewed with a mirror stereoscope

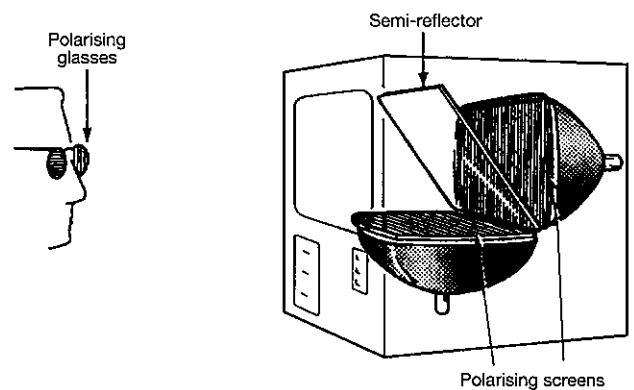


FIGURE 8 Twin monitors viewed with polarizing spectacles

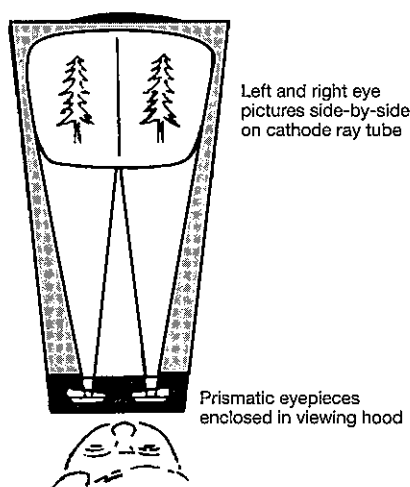


FIGURE 9 Single monitor with split-screen viewing

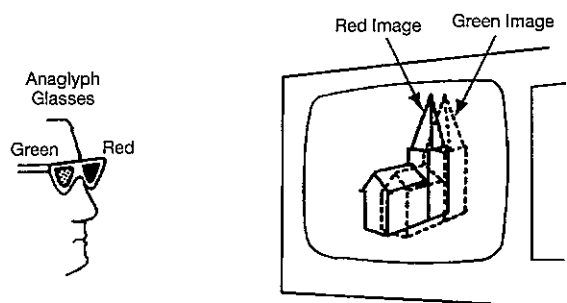


FIGURE 10 Stereo-viewing with anaglyphic spectacles

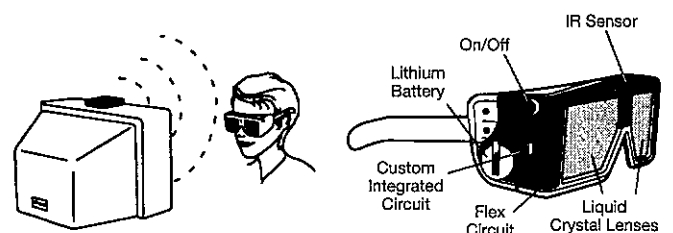


FIGURE 11 Alternating images on the monitor screen with alternating shutters for stereo-viewing

wiring to the display controller or by using an infrared emitter mounted on top of the monitor. Most DPWs using this technology have adopted the CrystalEyes system (from the StereoGraphics Corporation), which is based on the use of liquid crystal shutters and an infrared emitter. However, cheaper alternatives are now available from suppliers in the Far East. The system is widely used by Zeiss, Intergraph, VirtuoZo and Autometric/ERDAS, and as an option by Leica for its DPW 700 series. It is noticeable that the method is used mainly on those DPWs based on SGI graphics workstations, which are "stereo-ready", *ie*, they do not need additional hardware to implement the method.

(5) The last method also uses alternating (left/right) corresponding images displayed on a single monitor screen. In this case, however, each image has a different polarization pattern (clockwise/anti-clockwise) induced by an electronic prism mounted in front of the display monitor (Figure 12). Users viewing the stereo model wear spectacles equipped with the corresponding polarizing filters—these are described as "passive" spectacles to distinguish them from the so-called "active" spectacles acting as alternating shutters on the CrystalEyes system. The principal supplier of this type of viewing system is a Tektronix subsidiary, NuVision; the principal users are those DPWs driven by Sun SparcStations, *eg*, those supplied by Leica, Matra and DAT/EM.

It will also be noted that almost all these stereo-viewing systems allow several users to view the stereo-images simultaneously. Only those systems using mirror or lens stereoscopes restrict viewing to a single observer—although if required, this restriction could doubtless be overcome by using dual oculars, as was done with several types of analog stereoplotting instrument.

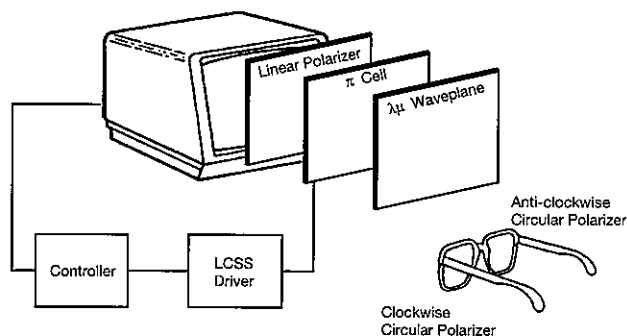


FIGURE 12 Alternating images on the monitor screen with an electronic prism in front of the screen; stereo-viewing using polarizing spectacles

MEASURING/POSITIONING DEVICES

A wide variety of devices are offered by the system suppliers to allow the operator to move freely through the stereo model and execute the various mensuration tasks that have to be carried out on a DPW. These tasks include measuring well-defined points such as fiducial marks, ground control points, etc, in a static mode, and the continuous stereoplotting required for feature extraction, contouring, etc, carried out in a dynamic mode. The most satisfactory devices appear to be those free-moving purpose-built controllers operating over high-resolution digitizing tablets, which were developed orig-

inally for analytical plotters [18], *eg*, the P-cursor used by Zeiss, and Intergraph's multi-button cursor (Figure 13). Similar controlling/measuring devices have been developed for DPWs, and indeed a common "3D mouse" that is used by Leica/Helava, Autometric and DAT/EM, while Matra uses the trackball (for planimetry) and thumbwheel (for height) arrangement previously used in its Traster analytical plotters [4]. Several system suppliers, *eg*, KLT Associates, ISM, etc, also offer handwheels and footdisks for high-precision pointing and map compilation, as used in traditional analog and analytical stereoplotters (Figure 15).

Some less expensive DPWs use the mouse and keyboard supplied with the system's computer for these tasks. To say that this is often a highly unsatisfactory method of controlling the position and elevation of the cursor would be a complete understatement—at least in the author's opinion! Indeed, the ergonomics and working environment of many current DPWs often fall a considerable way behind those provided by analytical plotters.

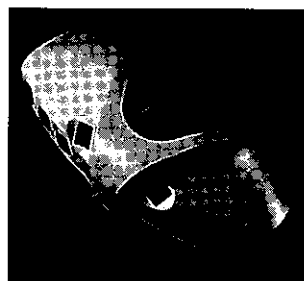


FIGURE 13 Intergraph's multi-button 3D measuring device as used on the InterMap digital (IMD) stereoplotter

CLASSIFICATION OF DPWs

Integrating all the individual hardware elements in different combinations has resulted in a large variety of DPW systems with differing capabilities, on offer at a wide range of prices. For convenience, these systems can be divided into three main categories (see Table 2):

(1) DPWs based on powerful high-specification RISC-based graphics workstations running under the Unix operating system and the X-windows GUI, which use the more elaborate and expensive types of stereo-viewing and purpose-built controlling/measuring devices (Figure 14). Needless to say, these DPW systems tend to come at the upper end of the price range. Apart from VirtuoZo, which is based on developments carried out at Wuhan Technical University of Surveying and Mapping (WTUSM) in China [23] and is now being marketed, distributed and supported by an Australian company, all system suppliers have been or are suppliers of analytical plotters using hard-copy images (*eg*, Leica/Helava, Intergraph, Zeiss, Matra, Autometric and DAT/EM).

(2) DPWs running on PCs under DOS and/or Windows. These are usually available at substantially lower prices than those available from the mainstream suppliers in category (1). Galileo/Siscam, Topcon and GeoSystems are smaller but still active suppliers of analytical plotters, whereas AMSA, ISM and KLT Associates (Figure 15) are software houses and mapping consultancies that have been producing conversion kits and software, respectively, for computer-based analog and analytical plotters. Two other suppliers, DVP Geomatics and R-WEL, are spin-off companies from

TABLE 2 Digital photogrammetric workstations

Category A (based on graphics workstations running under Unix OS)

	<i>Autometric Soft-Plotter</i>	<i>DAT/EM Digitus</i>	<i>Helava 750/770</i>	<i>Intergraph IMD</i>	<i>Matra Traster T10</i>	<i>VirtuoZo</i>	<i>Zeiss Phodis ST</i>
Computer	Silicon Gr	Sun Sparc	Sun Sparc	Inter 6000	Sun Sparc	Silicon Gr	Silicon Gr
Stereo-viewing	Alternating shutters	Polarizing filters	Polarizing filters	Alternating shutters	Polarizing filters	Alternating shutters	Alternating shutters
Measure	3D cursor	3D cursor	Trackball	3D cursor	Trackball	Mouse	3D cursor

Category B (based on PCs running DOS and/or Windows)

	<i>AMSA DC</i>	<i>DAT/EM Summit</i>	<i>Galileo/ Siscam Microdigit</i>	<i>Galileo/ Siscam Stereodigit</i>	<i>GeoSystem Delta WS</i>	<i>Intergraph Image St Z</i>	<i>ISM DiAP</i>
Stereo-viewing	Alternating shutters	Alternating shutters	Twin LCD	Twin monitor	Split screen	Alternating shutters	Alternating shutters
Measure	H/F wheels	3D cursor	Mouse	Mouse	H/F wheels	3D cursor	3D cursor
	<i>KLT Atlas/DSP</i>	<i>Leica DVP</i>	<i>Leica SOCET SET</i>	<i>PCI Image Wo St</i>	<i>R-WEL DMS</i>	<i>Topcon PI-1000</i>	
Stereo-viewing	Alternating shutters	Split screen	Polarizing filters	Polarizing filters	Anaglyph	Twin monitors	
Measure	H/F wheels	Digitizing tablet	3D cursor	3D cursor	Mouse	Mouse	

Category C (remote sensing systems suppliers)

	<i>ERDAS OrthoMAX</i>	<i>Microlimages TNT-MIPS</i>	<i>PCI EASI/PACE</i>
Computer	Sun/SGI	PC	Sun/SGI/PC
Stereo-viewing	Alternating shutters	Anaglyph	None
Measure	Mouse	Mouse	Mouse

universities (Laval and Georgia, respectively) that have well-known teaching and research programmes in the mapping sciences.

The newest additions to this group comprise PC-based DPWs with powerful dual Pentium processors running under the Windows NT operating system. This trend was started by the Canadian ISM company with its DiAP product. In spring 1997, however, similar offerings came from the two market leaders, Leica/Helava and Intergraph. The first comprises a Windows NT version of the GDE/Helava SOCET SET software, the port from Unix to NT having been carried out with assistance from PCI. As a result of this collaboration, PCI, as well as Leica, will offer a subset of the SOCET SET software under the title Image Works Stereo. In the case of Intergraph, the port of its Unix-based software has resulted in a new DPW product, Image Station Z. Summit PC, a somewhat similar but quite independently produced DPW also using Windows NT, has been



FIGURE 14 Leica/Helava DPW 770 (using a Sun SparcStation running under the Unix OS, and two monitors, one for stereo-viewing, the other for displaying system information, commands, etc). The Tektronix system with "passive" polarizing spectacles is used for stereo-viewing; a trackball is used for measurement



FIGURE 15
KLT Associates Atlas/DSP digital photogrammetric workstation (using a PC running MS-DOS and equipped with handwheels, a foot-disk, footpedals and a function keypad). Stereo-viewing can be carried out using either the CrystalEyes or Tektronix systems with alternating images or a split-screen viewing system

introduced by DAT/EM, which appears to be dropping its Unix-based Digitus DPW.

(3) DPWs produced by certain major remote sensing system suppliers (ERDAS, PCI and MicroImages), usually with an emphasis on DEM and ortho-image production from both aerial photographs and Spot stereo-images. To date, these DPWs have not really been optimized for feature extraction, apart from the on-screen digitizing of the detail shown on the ortho-images produced by the system. The OrthoMAX package, which forms part of the ERDAS Imagine system, is in fact a licensed and modified version of the DEM and ortho-image module from the Autometric/Vision SoftPlotter DPW.

ALGORITHMIC AND SOFTWARE ASPECTS OF DPWs

In purely algorithmic terms, the photogrammetric solutions used in the various DPWs are basically the same as those in analytical plotters using the object coordinates primary solution (Figure 16). They use a common basis of projective geometry and the same mathematical models; for example, the collinearity and coplanarity solutions for implementing standard analytical photogrammetric procedures are those used in DPWs. The inputs to the system from the operator's measuring device are therefore X,Y,Z object coordinates, and the DPW's real-time program generates as output the corresponding x,y positions of the cursor in pixel coordinates on each image of the stereo pair by using standard collinearity equations.

While all DPWs must be able to handle aerial photographs, quite a number are designed to also handle satellite images. Besides standard monoscopic Landsat and Spot images, several DPWs can handle the stereo pairs generated by the Spot and IRS-1C pushbroom scanners with their cross-track overlap. Without doubt, the future will see this capability extended to cope with the along-track stereo coverage that is being generated by both the MOMS-02 and JERS-1 OPS missions, and

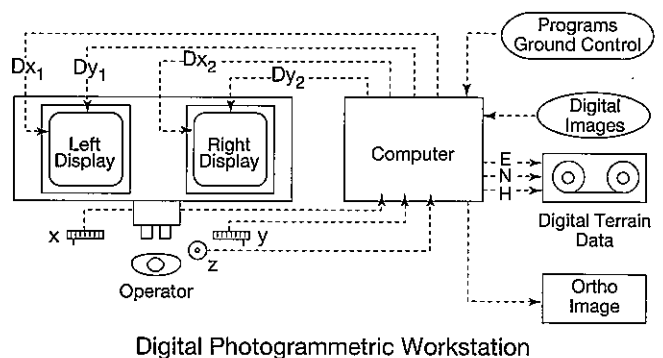
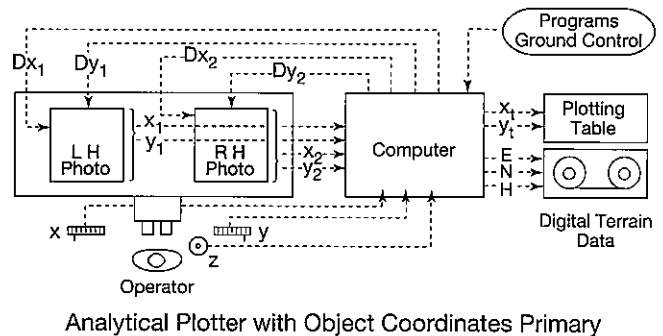


FIGURE 16 The algorithmic aspects of the DPW are similar to those of an analytical plotter with object coordinates primary because their basic system concepts are in principle the same

by the forthcoming American high-resolution commercial satellites such as Space Imaging (CCRS), Quick Bird and OrbView.

ORIENTATION SOFTWARE

Orientation procedures to produce a stereo model and fit it to the ground control points, thus bringing it into the required map projection system, are of course just as obligatory in DPWs as in analog and analytical stereo-

plotting instruments. Therefore, inner orientation via the measurement of the fiducial marks is a standard preliminary operation. In a DPW, the first one or two such marks often have to be measured manually before the remainder are determined using an image matching operation. However, fully automatic inner orientation, using image matching techniques in conjunction with a set of matching templates for different types of aerial camera, is now available from some DPW suppliers, *eg*, for Autometric's SoftPlotter [12].

Exterior orientation procedures can vary. Some systems use space resection of individual photographs, followed by space intersection based on a bundle adjustment. However, the classical sequential relative and absolute orientation procedures are still being used in various DPWs, ranging from the Leica/Helava and Zeiss Phodis at the top of the market to the TNT-MIPS systems offered by the remote sensing system supplier MicroImages. Within this approach, automatic or semi-automatic relative orientation modules have been provided for several DPWs [7]. However, absolute orientation almost always requires operator interaction to identify the ground control points.

The intrusion of suppliers with no previous photogrammetric background can be seen when ground control points for absolute orientation can be measured only by monocular measurements on each image of the stereo pair or by monocular pointing on one image, followed by automatic image matching of the corresponding point on the overlapping image. In such cases, the advantages of making stereo measurements in 3D or using them to check the accuracy of pointing have been either overlooked or discarded. The impression of a comparative lack of knowledge or experience is reinforced when, on some systems, the results of fitting the stereo model to the ground control points (*ie*, the absolute orientation) are declared only after the processing of the resulting DEM has been completed—often some hours later! In such cases, there is apparently a lack of awareness that there is no point in even starting the DEM image matching process if the absolute orientation is defective.

TRIANGULATING SOFTWARE

In the case of aerial or space triangulation, the data acquisition procedures carried out in the DPW are again similar to those followed in an analytical plotter, with point selection, point transfer, point measurement, model formation and checks for blunders being conducted on a model-by-model basis along the strip. Again image matching capabilities may be provided—often using an area- or feature-based matching procedure based on an image pyramid, with correlation carried out at successive levels until the finest level is reached at which image digitization has taken place. Such procedures are certainly more effective when fiducial marks, signalized points and well-defined features are used rather than less well-defined natural points; for the latter, and especially for featureless areas, a manual stereoscopic measuring capability is still required. If image matching techniques can be applied to the transfer of tie-points and control points and their subsequent measurement, the gains in productivity can be impressive [14].

Once the measurement phase has been completed, the software available on most DPWs for the model, strip and block formation and the subsequent adjustment is

usually one of the well-established block adjustment programs, such as PAT-M, PAT-B or BLUH, developed for use with analytical instrumentation. Current versions of these programs can use airborne kinematic GPS measurements of the exposure stations, now that these are becoming more common. The finally adjusted values of the coordinates of the triangulation tie-points and perspective centers, and the image rotations and translations can then be produced as headers or support files for each digitized image in order to assist in setting up individual stereo models for subsequent map compilation and DEM and ortho-image production.

MAP COMPILATION SOFTWARE

Here again, the tendency is to incorporate into the DPW well-established third-party software packages that were developed originally to support analog and analytical stereoplotters in the acquisition of photogrammetric data (feature extraction) for input to digital mapping, CAD and geographic information systems. Typical of these packages are ATLAS from KLT Associates; KDMS from Kork Systems (now part of the Autometric/Vision International group); DWG/CAPTURE and DGN/CAPTURE from DAT/EM; PRO 600 from Leica; CADMAP (now owned by Zeiss); etc. All these packages offer feature coding and the input of attribute data, as well as on-line interfaces and data transfer to the Bentley Systems/Intergraph MicroStation package, which is currently the prime system for structuring and editing photogrammetrically captured vector data. Once this has been completed, the structured and edited data are transferred to the digital mapping, CAD or geographic/land information system, using a standard protocol such as DXF.

To date, there has been little sign of automatic feature extraction reaching production status, despite the intensive research work undertaken in this field in recent years. At the moment, so many errors and omissions occur in this automated process that the subsequent extensive time-consuming editing process is impractical and uneconomic to implement. Operator interaction with the system is therefore still obligatory if point features and vector line data are to be extracted for digital map production or input to a CAD or geographic/land information system. However a few semi-automated tools have been introduced (*eg*, by Leica/Helava) for squaring buildings, line following and region building to assist the operator with feature extraction, with a view to reducing fatigue and increasing productivity.

SOFTWARE FOR DEM PRODUCTION

There is little doubt that the automatically generated DEM data and the digital ortho-images derived from them have been the main products arising from the development of digital photogrammetric systems. All DPWs contain software to implement these operations. In this context, there are also several products (*eg*, Zeiss Phodis TS (for DEMs) and OP (for digital orthophotos); Galileo/Siscam Orthomap, PCI OrthoEngine and Vexcel OrthoGIS (for digital orthophotos); Inpho Match-T (for DEMs); etc) that are simply dedicated to these tasks, and which are sold as stand-alone systems to carry out these operations. Thus they do not possess the full functionality of a DPW, and consequently carry a much lower price-tag than that attached to a full-blown DPW system.

The Match-T product is offered by Intergraph and DAT/EM and underlies part of the Zeiss Phodis TS system, besides being offered as a stand-alone product by the developer, Inpho GmbH.

It virtually goes without saying to experienced photogrammetrists that failures occur—at least to some extent—during all automatic DEM operations. In areas with few well-defined features, which exhibit poor contrast and little texture, more severe difficulties can occur. In general, the software used for automated DEM data generation works best at medium scales and in areas for which images with good texture are available. At larger scales, difficulties arise from occluded/dead areas and height discontinuities attributable to the presence of tall buildings and forests in the areas being mapped. Therefore, the key to successfully implementing the whole process is the provision by the software package of the interactive editing facilities needed to correct the inevitable errors in the DEM data. One would expect these to include stereo-superimposition facilities to enable the operator to discover the errors in the DEM and the areas of poor matching, and a stereo-mensuration capability to make the required corrections to the elevation data. The fact is, however, that certain packages used in DPWs (eg, some provided by remote sensing system suppliers) do not provide such facilities. The required editing is then problematic to say the least, and virtually impossible in some situations—as the author can testify with some feeling!

In addition to the automatic image matching technique, some DPWs are also provided with software with the capability of driving the cursor to a series of pre-specified terrain positions. This is done usually on a grid basis—as is standard with mainstream analytical plotters carrying out systematic sampling [17]. The elevation measurements can then be carried out either by image matching (when suitable conditions apply) or manually in stereo by an operator. In the latter case, these measurements are supplemented by selective sampling via the measurement of breaklines and other important topographic features in order to provide a more complete DEM on the basis of a composite sampling strategy. Needless to say, providing an interface and data transfer facilities to connect the DPW to well-established DTM systems (which can provide contouring, cross sections, profiles and perspective views based on the DEM data, and merge the DEM data from individual stereo models into a single seamless array) should be obligatory. Sometimes, however, these are not provided.

SOFTWARE FOR DIGITAL ORTHOPHOTO PRODUCTION

Turning next to the generation of orthophotographs and ortho-images, virtually every DPW system supplier provides this capability. However, the procedures used do vary somewhat in their effectiveness. Some provide a completely rigorous solution over the whole stereo model; others appear to implement a somewhat less rigorous procedure by differentially rectifying only a specific grid of points, with the image areas between these points being rectified (it seems) using an interpolative procedure.

The high-resolution digital orthophotograph of the terrain produced by a DPW can act as an informative raster image backdrop (or backcloth) in geographic/land infor-

mation systems, on which existing vector data can be easily superimposed. It is also possible to carry out the vector digitizing of features in the orthophotographs through “head-up” digitizing on screen, either for map revision purposes or for input to geographic/land information systems.

A notable feature of some DPW orthophoto software modules is the ability to carry out mosaicking of the individual images generated from the stereo pairs. This operation may include radiometric processing via enhancement and filtering routines to equalize the contrast between individual component images. The most sophisticated may even attempt geometric and radiometric feathering of the adjacent images to provide a seamless final composite image. However, this time-consuming mosaicking procedure will not infrequently be carried out off-line on a dedicated editing station rather than on the DPW used for the data acquisition. Furthermore, many users supplement the image processing routines included in the packages provided by system suppliers with those provided by a general-purpose package such as Adobe Photoshop. Finally, it is worth noting that roof correction software (to correct for building lean) for use with orthophotographs of urban areas is a recent innovation from Leica/Helava.

OUTPUT FROM A DPS

This article aims to present the whole digital photogrammetric system and, since the input side—including scanners in some detail—has already been dealt with, it seems logical and consistent to give some consideration to the output devices that produce hard copy from the digital data generated by DPWs.

In the first place, the traditional type of high-accuracy flatbed plotting table (coordinatograph) based on the use of vector data (eg, the Wild Aviotab and Zeiss Planitab) still has a role to play, more especially at very large scales in applications such as cadastral mapping and engineering surveys where accuracy is paramount. Less accurate are the vector-driven sheet-fed drum or roller plotters, which tend to be used as edit plotters. All these devices can be attached either directly to the DPW or—more commonly nowadays—accessed over a network via a plot server, thus providing a resource that can be shared by several DPWs or analytical plotters.

Nowadays, the output side is dominated by raster-based devices, even when the data generated by the DPW are produced in vector form. In such a situation, the vector data will need to be rasterized before being sent to the plotter. However, because much current DPW use is concentrated on the direct output in raster format of DEM data and ortho-images, the use of raster-based devices becomes obligatory. A wide range of alternative competing technologies is now available. A number of these printer/plotter devices that can generate colour prints, using either (1) colour wax transfer, (2) colour dye sublimation or (3) colour laser technology, are confined to mainly small formats, usually A4 or its American equivalent. Thus they can be used to generate reasonably high-quality presentation graphics but are not suitable for the vast majority of mapping and GIS applications, which require larger formats. Therefore, attention will be focused here on those devices that can generate large-format hard-copy output.

The principal available devices can be conveniently grouped under the following headings: (1) electrostatic, (2) inkjet, (3) thermal, (4) laser and (5) film plotters.

ELECTROSTATIC PLOTTERS

This is a relatively mature and well-developed technology that can handle large formats (up to 36 inches (90 cm) and 44 inches (120 cm) in width, with effectively no limitations in length) and generate map images at moderate resolutions (300 dpi) in either monochrome or colour. These plotters are available from suppliers such as Xerox/Versatec, Calcomp, Oce/Benson and Precision Image. The colour electrostatic plotters include competing single-pass and multiple-pass technologies for generating colour hard copy on both film and paper. The purchase prices of these devices are relatively high, but visits to mapping agencies confirm that they continue to be used to generate edit plots, colour proofs and those map products required in small numbers (*ie*, requiring short runs) for reports.

INKJET PLOTTERS

To a substantial extent, this is the technology that has taken over the role from the electrostatic plotters of providing reasonable quality output in monochrome or colour. At one end of the scale, there are a large number of inexpensive small-format inkjet plotters on the market, which deliver a reasonable quality of output at resolutions between 300 and 600 dpi. Variations in the basic technology include:

- the drop-on-demand type (tiny ink particles are ejected through a nozzle onto paper or film through the action of a piezo-electric crystal)
- the bubblejet type (tiny heating elements are incorporated in the nozzle and some ink is volatilized to form a gas bubble, which again ejects an ink droplet onto the plotting medium)
- the solid inkjet (or phase change) device (solid ink sticks are melted by heating before the ink droplets are ejected).

These devices compete successfully with the other types of small-format colour plotter (thermal wax and laser) noted above, especially given their lower purchase prices.

However, the larger-format inkjet plotters are of most interest to mapping organizations. A monochrome version that enjoys widespread use is the Hewlett Packard DesignJet, which can accommodate either cut sheets or 24-inch (60 cm) or 36-inch (90 cm) wide rolls of paper or film, plotting at resolutions up to 600 dpi. The ENCAD Novajet is a similar type of colour inkjet plotter. Both these devices have become very popular with mapping agencies. Indeed, their comparatively low purchase prices and reasonable performance are fast making them the dominant plotter technology at low to medium resolutions, capable of producing image maps, as well as vector line maps, of acceptable quality.

At the top of the price and quality range are the inkjet plotters produced by Iris Graphics in a variety of format sizes (10.6 x 17 inch (27 x 44 cm); 24 x 24 inch (60 x 60 cm); 34 x 44 inch (84 x 112 cm)). These use a sophisticated type of inkjet technology, combining variable dot size and dithering to achieve excellent quality on either film or paper (Figure 17). Needless to say, the Iris products cost considerably more than the

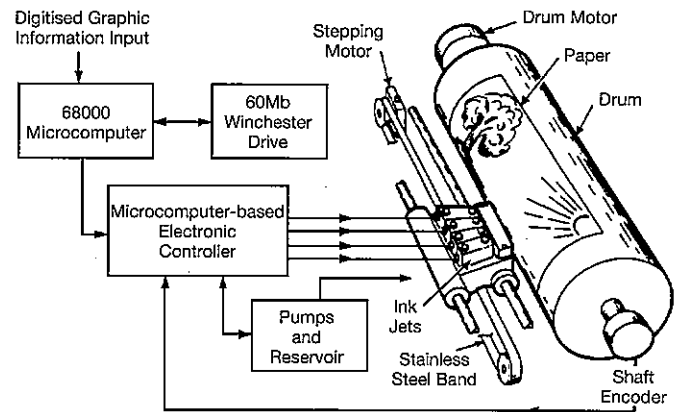


FIGURE 17 Iris Graphics large-format inkjet plotter

DesignJet or Novajet devices, but the extra cost is justified if very high quality is required, *eg*, for image maps.

THERMAL PLOTTERS

These plotters, available from, *eg*, Hewlett Packard, Oce and Rikadenki, use a linear thermal writing head covering the whole width of the sheet of heat-sensitive paper or film. This head 'sweeps' across the sheet and plots out the map only in monochrome at reasonable resolutions (400 dpi). More recently, bicolour media have been introduced, allowing the generation of both black and red—a most useful feature, *eg*, for showing up revision detail on large-scale maps.

LASER PLOTTERS

In addition to the small-format colour laser plotters noted above, there are also high-quality large-format laser plotters, such as the Versatec 8836, which produce plots in monochrome only. Thus they compete with the monochrome inkjet and thermal plotters, although they tend to be less widespread because of higher costs.

FILM PLOTTERS

Because the DPW is currently much used to generate orthophotographs and ortho-images, the matter of using film plotters that can fully retain the intrinsic resolution of the original images has increased greatly in importance. One approach is to generate continuous-tone negative film images on film writers, which are rotary drum plotters analogous to rotary drum scanners (Figure 18). Typical are those sold by Kodak (LVT), SEP (Vizir) and Intergraph/Optronics, and the Macdonald Detwiler/Cymbolic Sciences Fire series. These allow only a limited format size to be produced (typically 10 x 12 inch (25 x 30 cm)), but at high resolutions (*eg*, 2500 dpi). From these negatives, high-quality enlargements of the final image can be produced on photographic film or paper, using a conventional photographic enlarger.

The alternative approach is to use a large-format raster film plotter (*eg*, Barco's MegaSetter or BG-3800 (Figure 19), the Agfa SelectSet, Intergraph's Mapsetter), using either an argon or helium neon laser or an LED light source to write the image on a large-diameter rotating drum. Usually, an automatic film processor is coupled directly to the output channel of the plotter. Table 3 lists some devices currently available on the market, together with their main characteristics. These plotters