S6444

Distr.: LIMITED

ECA/NRD/CART.9/ORG.14
October 1996

Original: ENGLISH

Ninth United Nations Regional
Cartographic Conference for Africa

Addis Ababa, Ethiopia
11-15 November 1996

Development in Digital Photogrammetric Systems for Topographic Mapping and GIS/LIS Applications

DEVELOPMENTS IN DIGITAL PHOTOGRAMMETRIC SYSTEMS FOR TOPOGRAPHIC MAPPING AND GIS/LIS APPLICATIONS

Gordon Petrie
University of Glasgow

ABSTRACT

This paper sets out the current situation in the development of digital photogrammetric systems (DPS) as applied to the field of topographic mapping and GIS/LIS applications. It includes the devices used for input to and the 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 which have to be handled are first discussed in some detail. This discussion is followed by a review of the photogrammetric quality scanners currently available on the market. Next, the hardware aspects of the DPW are discussed, including processors, data display, stereo-viewing and measuring/positioning devices. A classification of present DPWs is then made and is accompanied by a table setting out the main characteristics of those systems which are available commercially. The paper then goes on to discuss 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 including 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.

---

1. Introduction

The last ten or twelve years have seen the steady development of Digital Photogrammetric Systems (DPS) moving first from the individual pioneering systems devised by research groups in certain European universities, and the specialised systems produced for military intelligence and mapping agencies in the United States to the first commercially marketed Digital Photogrammetric Workstation (DPW), the Kern DSP 1, shown at the XVI ISPRS Congress held in Kyoto in 1988. Since then, the momentum has increased with the advent of a wide range of systems from a variety of suppliers featuring ever greater capabilities. This development first became apparent at the XVII ISPRS Congress held in Washington in 1992. Since then, in the four years leading up to the XVIII ISPRS Congress held in Vienna in 1996, the pace of development has increased further. 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 of the technology, only since 1994 have the systems begun to be sold in any real numbers. In Europe, a few, mainly government mapping organisations such as the Ordnance Survey of Ireland (Miller, Walker and Walsh 1995; Kirwan, Miller and Walker 1996), the Institut Cartografic de Catalunya (Colomar and Colomina 1994) and Lantmäteriverket in Sweden (Johansson, Miller and Walker 1995) have embraced the new technology in a fairly comprehensive fashion, albeit to supplement a still considerable analytical plotter capacity. However, more commonly, 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 with it before increasing their commitment, as in the case of the Canada Centre for Topographic Information (Armenakis, Regan and Dow 1995). Undoubtedly the greatest success of the DPS till now 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 utilising hard copy photographs have 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 SD-2000/3000 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 present author (Petrie 1992) reviewed the field in detail in 1992, the only new analytical plotters to appear have been the Adam Technology Promap from Australia and the Stereoanagraph-6 from the new Ukrainian supplier, GeoSystem. However there still seems to be considerable activity in converting analogue stereoplotters to their analytical plotter equivalents, e.g. using the conversion kits offered by Qasco and Adam Technology. There is also a 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 desk-top computers or work stations that they were supplied with. Conversion kits for this purpose are on offer by DAT/EM, AB Software Developers, etc.

When comparing the two technologies, the great advantage of the digital photogrammetric workstation (DPW) is that it eliminates all expensive high precision mechanical components of the analytical plotter such as its photo stages, carriages, lead screws, etc., together with their associated measuring components such as linear or rotary encoders. Also most of the high-quality optical components of the analytical plotter are not required, though many of the higher-end DPWs feature stereo-viewing systems that are quite costly items to incorporate in the workstation. Indeed the more sophisticated and capable DPWs based on high-performance graphics workstations are still quite expensive to purchase - at the present time, they cost more than the corresponding analytical plotter. However this cost should reduce in future and there also exist, as with analytical instrumentation, less capable but also much less expensive DPWs which can satisfy the needs of many less demanding users.

1.1. Basic Elements of a Digital Photogrammetric System (DPS)

The main characteristics of such a system (Fig.1) are as follows:-

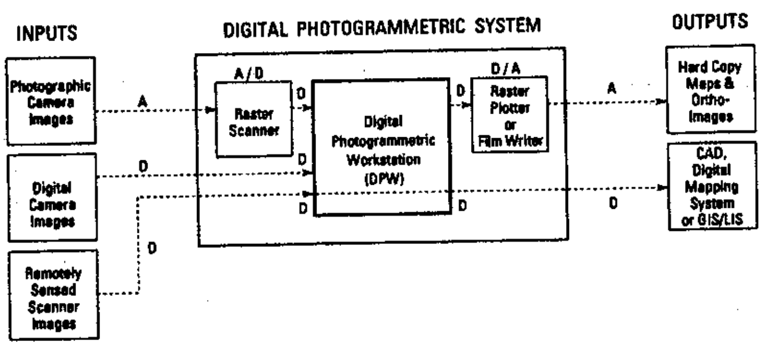


Fig. 1 - Overall Concept of Digital Photogrammetric System.

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

(b) These operations are carried out on sets of image data consisting of picture elements (pixels) of a fixed shape and size. Each individual pixel has a brightness value (BV) assigned to it which gives the value of the radiance from the object field falling on each individual element of the imaging sensor.

(c) The imaging sensor itself may take the form of
  (i) a digital camera equipped with an areal array of charge-coupled detectors (CCDs); or
  (ii) 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 analogue-to-digital (A/D) conversion of the radiance which is measured electrically for each individual element of the sensor.

(d) However, for topographic mapping operations, digital image data is 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 using high-precision scanners equipped with linear or areal CCD arrays. In this case, the scanner forms a vital and integral part of the Digital Photogrammetric System (DPS).

(e) The main element of a DPS is the Digital Photogrammetric Workstation (DPW) on which the required analytical (i.e. numerically- and mathematically-based) photogrammetric operations are carried out to produce data for input to
- (i) digital mapping systems;
- (ii) CAD systems; and
- (iii) GIS/LIS systems.

(f) These photogrammetric operations include
- (i) manual (operator-controlled) operations such as the feature extraction involved in map compilation and revision; and
- (ii) automatic or semi-automatic operations such as the generation of Digital Elevation Model (DEM) data and ortho-image data.

(g) Final output may take the form of
- (i) vector line maps;
- (ii) Digital Terrain Model (DTM) data; or
- (iii) digital ortho-images.

In which case, 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 are carrying out a digital-to-analogue (D/A) operation.

In view of these specific characteristics set out above, this paper will review developments in each of the four main elements of a Digital Photogrammetric System (DPS) - the acquisition of digital image data from different imaging sensors; the scanner technologies involved in digitizing photographic images; the DPW itself; and the main output devices - as used in the field of topographic mapping. Non-topographic applications will not be covered in this paper.

2. Image Data Acquisition and Input to a DPS

There is a vast range in the volume of digital image data that comes from different sensors and has 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; mostly they are encountered in close-range photogrammetric applications. A typical video or CCD areal array camera generating a black and white (grey-level) image will have an imaging area of 512 x 512 pixels = 250,000 pixels or 0.25 megapixels requiring 0.25 Mbytes storage (where the data for one pixel requires one byte of storage). A higher resolution camera with 1,000 x 1,000 pixels would give rise to 1 Mbyte of data; and a really high resolution camera of 2,000 x 2,000 pixels (which is still as yet uncommon) would generate 4 megapixels and require 4 Mbytes of storage.

Considering next the pushbroom scanners commonly used in remote sensing 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 6,000 x 6,000 pixels = 36 megapixels requiring 36 Mbytes storage; while the SPOT XS imager generates 3,000 x 3,000 pixels giving a 9 megapixel image per spectral channel, so requiring 27 Mbytes of storage for a three-channel false-colour image or scene.

Coming finally to the standard aerial photogrammetric camera with its 23 x 23cm 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). Since both theoretical and practical considerations indicate that 2 pixels are needed to represent 1 line pair (Welch 1993), this equates to pixel sizes between 25μm and 12.5μm (Fig. 2). The latest high-performance cameras equipped with forward motion compensation (fmc), gyro-controlled stabilized mounts and high resolution film (such as the Wild RC-30 or the Zeiss RMK-TOP) give 60 lp/mm, which is equivalent to a pixel size of 8.5μm. Thus photogrammetric quality scanners which convert the film image to digital form must provide a minimum pixel size of 8 to 10μm if the resolution inherent in the negative film is to be preserved.

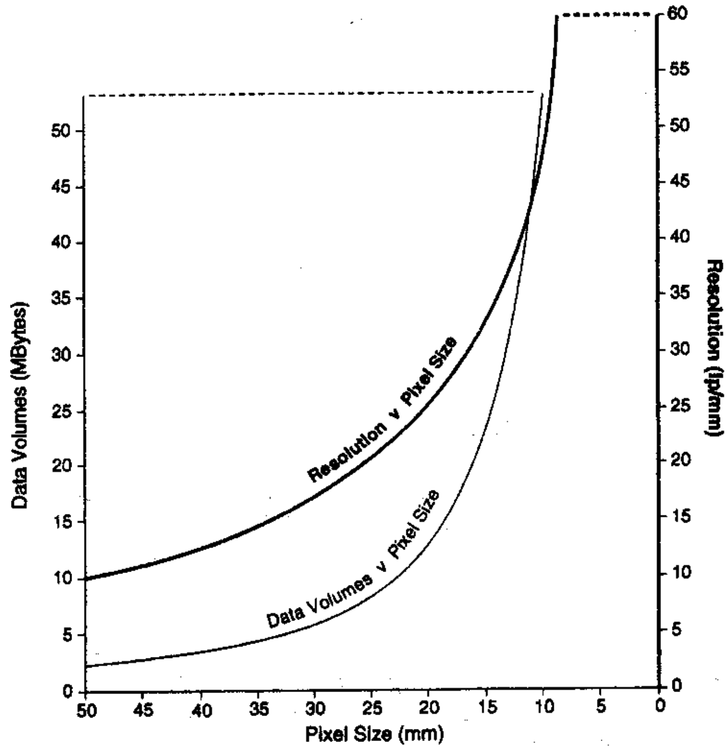


Fig. 2 - Resolution and Data Volumes Resulting from Scanner Pixel Size.

Regarding data volumes, if the monochrome film resulting from the use of an aerial camera is digitized at a pixel size of 25µm, i.e. 1,000 dots per inch (dpi), equivalent to 20 lp/mm, this would give rise to 9,200 x 9,200 pixels = 85 megapixels (85 Mbytes). With a 15µm sampling interval, the data increases to 235 megapixels, while with a 10µm pixel, i.e. 2,500 dpi, the data increases to 529 megapixels (or 529 Mbytes) per image (Fig. 2).

Since most photogrammetric operations involve the use of stereo imagery, a pair of standard aerial photographs will generate in excess of 1 gigabyte (1Gbyte) of data at the 10µm 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. Thus image compression/decompression techniques such as JPEG have been offered and used as a way of alleviating some of the problems associated with these large data volumes. Even then, the use of RAID technology with capacities of 50 to 100 GBytes is not uncommon in those mapping agencies that have adopted a DPS.

3. 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. This digitization is provided by a scanner, which will normally use one or other of the four main technologies (Fig. 3) currently available for use with stable transparent film images. These comprise:-

(1) the use of a rotating drum scanner equipped with a scan head;

(2) the use of a 2-D 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;

(3) the use of a 1-D scanning linear array of CCDs which scans the photo in a single sweep;

(4) use of a CCD areal array - often described as a CCD camera or staring array - allowing patch-by-patch scanning of the photographic image with re-assembly of the patches later into a single seamless image.

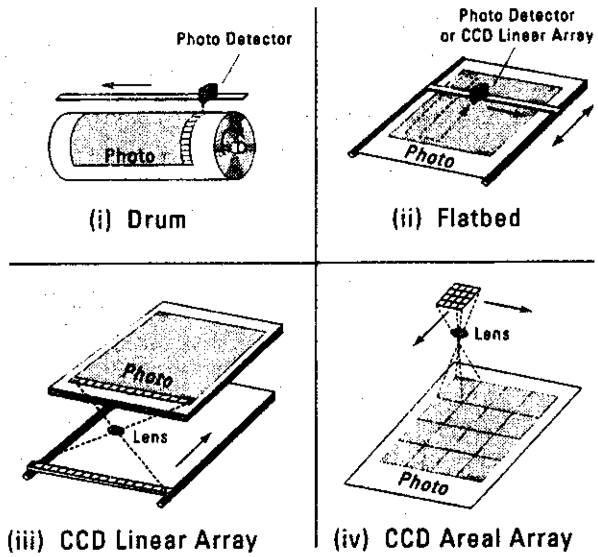


Fig. 3 - Principal Scanner Technologies

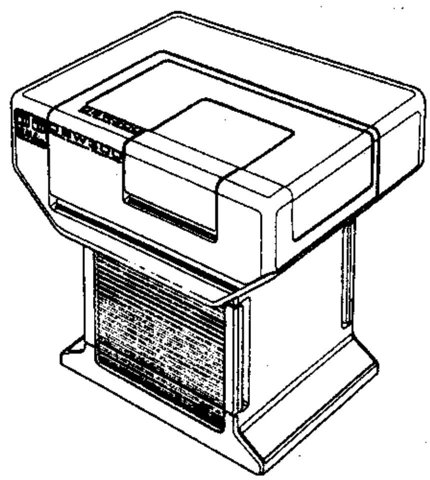


Fig. 4 - Leica/Helava DSW Scanner

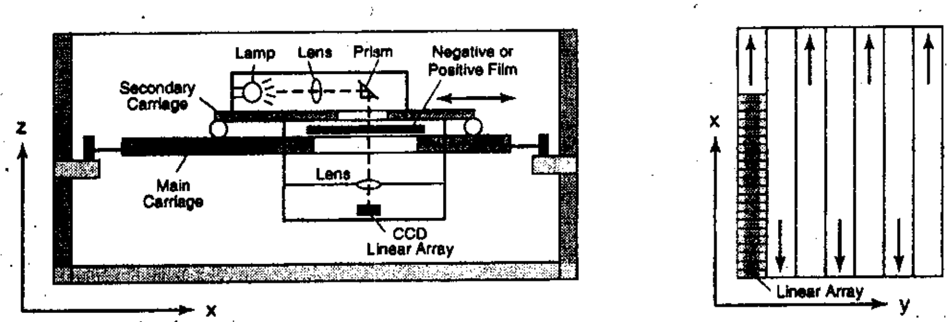


Fig. 5 - 2-D Flatbed Scanner Equipped with a CCD Linear Array.

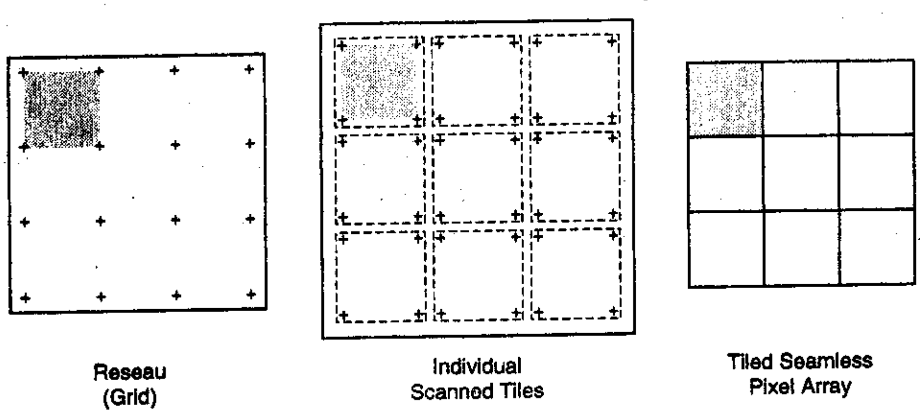


Fig. 6 - Use of a CCD Areal Array with Patch-by-Patch Scanning and Transformation of the Tiles or Patches into a Single Seamless Pixel Array.

Arrangement (1) has been used by the Optronics, Hell and Crosfield film digitizers utilised extensively in the graphic arts world. The 2-D flatbed scanner [type(2)] arrangement is quite commonly used in purpose-built photogrammetric scanners, most notably the Zeiss/Intergraph series, but also the Wehrli RasterMaster and the ISM DiSC. The third type (3) in which a linear CCD array scans the image in a single sweep is used only by the XL Ortho Vision, while the fourth arrangement (4) utilizing the areal array or CCD camera is that employed in the Leica/Helava DSW series and in the Vexcel, Lenzer, Rollei and Topcon scanners.

A high accuracy of the scanner is obligatory if the introduction of errors to the geometry of the photographic image is to be avoided. Thus the photogrammetric requirements of these scanners call for linear measuring resolutions of 1 to 2µm and accuracies (RMSE) of ±3 to 5µm on each axis together with minimum pixel sizes of 8 to 10µm (2,500 dpi). In other words, the same accuracy requirements apply as for a monocomparator or a mainstream analytical plotter. Typically the time taken to scan a single black and white (monochromatic) photograph lies in the range 5 to 20 minutes for a 23 x 23cm image at pixel sizes of 10 to 15µm, using a powerful PC or graphics work station equipped with sophisticated software to carry out the necessary control and storage functions. These functions will often include the automatic measurement of the fiducial marks for inner orientation using image matching techniques.

On the radiometric side, the digital image data is normally produced in an 8-bit form providing 256 levels in terms of grey scale. However some recent scanners offer 10-bits (1,024 levels) in terms of their internal digitization, though 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 motorised RGB colour wheel (utilised by the Wehrli RasterMaster, Vexcel, etc.) or a tri-linear CCD arrangement (employed in the Zeiss/Intergraph SCAI/TD scanner) to ensure the required colour separation of the image.

While most of the earlier scanners were designed for use with positive film transparencies (diapositives) only, this meant that a considerable time and expense was incurred in making film diapositives from the original negative roll film, before scanning could take place. This was a serious matter if a large number of photographic frames had 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 has its own difficulty in that the production of the individual diapositive did allow dodging of the image to take place to improve its contrast and interpretability. So scanners that can handle negative roll film, e.g. the Leica/Helava DSW 300 (Fig. 4) 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. Their main characteristics are set out in Table I.

The Zeiss/Intergraph series may be taken as representative of the type (2) scanners. The PS-1 uses many of the mechanical components (ways, encoders, etc.) of the Planicomp P3 analytical plotter (Mayr 1992), 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. The newer SCAI (Zeiss) or TD (Intergraph) models have a larger range of pixel sizes and an improved grey level range and are driven by Silicon Graphics (Zeiss) and PC (Intergraph) workstations respectively. However the principal change over the earlier PS-1 series is 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. A further change is that the light source, optics and CCD linear array now move as a unit against the fixed position of the film on a register glass (Fig. 5).

	GeoSystem Delta Scan	ISM DiSC	Leica Helava DSW 100	Leica Helava DSW 200	Leica Helava DSW 300	Lenzar Lenzpro 2000/2001
Scan Area (cm)	30x30	25x25	25x25	26.5x26.5	27x27	30x30
Linear Res (μm)	1	1	1	1	0.5	0.25
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
Grey Levels	256	1,024	256	256	1,024	256/1,024
CCD Sensor	2,048x1	8,000x1	1,270x1,270	2,029x2,044	2029x2044	Patch
Roll Film	No	Yes	No	?	Yes	Yes
Computer	PC	PC	Sun/PC	Sun	Sun	SGI/Sun

	Rollei-metric RS	Wehrli Raster-Master RM1	XL Ortho Vision	Zeiss/ Intergraph PS-1	Zeiss Intergraph SCAI/TD
Scan Area (cm)	22x22	24.5x24.5	23x23	26x26	25x27.5
Linear Res (μm)	1	0.5	1	1	1
Accuracy (μm)	?	±4	±3	±3	±3
Pixel Size (μm)	12x18	12 to 96	9 to 73	7.5 to 120	7 to 224
Grey Levels	16 of 256	256	256	256	1,024
CCD Sensor	604x576	2,048x1	24,000x1	2,048x1	5,632x1
Roll Film	No	No	Yes	No	Yes
Computer	?	PC	PC	Interpro	SGI/PC

Table I - Digital Photogrammetric Scanners

The Vexel VX 3000 may be taken as representative of the type (4) scanners, though its format of 25 x 50cm is exceptional, being designed to accommodate the large format (23 x 46cm) cameras used by U.S. military mapping and reconnaissance agencies. A CCD areal array camera is driven over the photograph to be scanned and does so with reference to a precision grid or reseau (Leberl, Best and Meier 1992). The latter is first scanned and the coordinate positions of the grid intersections determined. Subsequent to this, the image is scanned in a series of patches or tiles. The final stage is the transformation of the individual tiles into a seamless pixel array (Fig. 6) using the known reseau positions.

It is interesting to note that, with the relatively small numbers of DPWs in many mapping organisations and the relatively high cost of a photogrammetric quality scanner, a number of scanning bureaux have been established in various countries. These even offer a scanning service to their competitors in the mapping field since this helps them to recover some of the costs of purchase and operation of these high performance devices.

There are of course numerous lower-cost scanners capable of converting hard copy prints into digital images. These have mostly been developed for use in the desk-top publishing industry with scanning resolutions in the range 300 to 600 dpi (80 to 40μm resolution). This leads to the generation of data having a much larger minimum pixel size than that compatible with the resolution of the aerial photograph. However, from the photogrammetric point of view, they have various other limitations besides the lower resolution and larger pixel size. These include a restricted 4 or 6-bit grey level range; and the fact that they are often designed to accept prints only and cannot handle film transparencies. Furthermore they are often built to accommodate the standard A4 page format (21 x 25cm) and thus they cannot accommodate standard 23 x 23cm format aerial photographs, which need to be digitized in two separate operations. A further limitation of low-cost scanners is their geometric accuracy - Ehlers quotes ±2.4 pixels even at the rather crude scanning resolution of 80μm pixel (300 dpi). Data produced with such a device cannot normally be used for serious photogrammetric work, although if it could be calibrated in an appropriate manner and had an appropriate format size, this might be possible.

4. Digital Photogrammetric Workstations

The Digital Photogrammetric Workstation (DPW) consists of a graphics workstation with enhanced image processing, memory and display capabilities, including, in most cases, but not all, a stereo-viewing facility, and with appropriate software to allow photogrammetric operations to be undertaken.

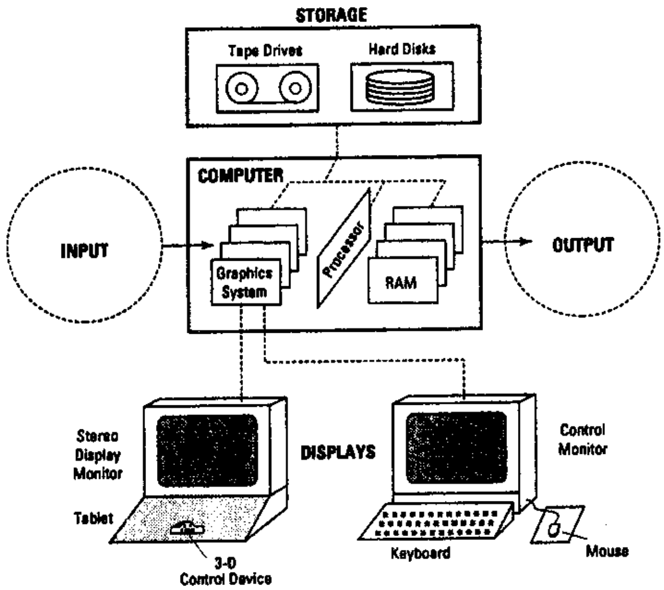


Fig. 7 - Main Elements of Digital Photogrammetric Workstation.

4.1. Hardware Aspects of the DPW

The main features of the hardware utilized in a DPW (Fig. 7) may be set out as follows:-

(a) A powerful processor (CPU) and a very large memory (RAM) are required to handle the large volumes of image data which are an inherent feature of a DPS.

(b) Usually an additional or supplementary processing capability is required to ensure the timely execution of computationally intensive tasks, e.g. automatic image matching for the measurement of digita' elevation model (DEM) data. This additional capacity may be provided through the use of one of the following:-
(i) a graphics accelerator;
(ii) a digital signal processing (DSP) board; or
(iii) an array processor.

(c) Very large data storage needs to be provided - high capacity hard disks and back-up storage devices (in the multi-gigabyte range) are required to store the image data.

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

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

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

4.1 Computer Hardware Aspects

With regard to processors (CPUs), the graphics workstations which form the basis of DPWs at the top end of the performance scale use RISC (Reduced Instruction Set Computer) processors almost exclusively. The two most common types by far are the Sparc processors employed in the Sun SparcStation and Ultra Sparc workstations and the MIPS processors used in the Silicon Graphics (SGI) Indy and Indigo workstations. These two brands of workstation are utilized by the traditional mainstream photogrammetric system suppliers, - e.g. Leica/Helava (both Sun and SGI); Zeiss and Autometric (Silicon Graphics) and Matra (Sun). So far, the comparable alternative RISC processors from DEC (Alpha) and Hewlett Packard (PA) have not been adopted for use in DPWs to any substantial extent - though Leica/Helava have delivered a few of their DPW 770 model with Hewlett Packard workstations. Intergraph uses its own proprietary Clipper RISC technology in its Interpro workstations. However the company appears increasingly to be using Pentium-based PCs (often with two or four processors coupled together) in its other product lines, so it may only be a matter of time before this policy reaches its DPW. Many of the smaller DPW suppliers, e.g. R-WEL, ISM, DVP, KLT, etc. have already based their systems on PCs.

As far as memory is concerned, 32 Mbytes of RAM is the minimum, 64 Mbytes is common and 128 Mbytes 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 through the use of hard-disks of multi-gigabyte capacity 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 both the CDs on which the data suppliers frequently supply image data and those containing the system software delivered by the DPW supplier. The back-up and archiving of data is normally carried out using compact tape drives employing DAT or Exabyte data cartridges.

Regarding graphics accelerators, these have a special place on DPWs, principally to assist with the implementation of stereo-viewing, with its need for rapid refresh rates, especially in those systems employing alternating imaging on the display screen for the purpose of stereo-viewing. Also they assist with image roaming over the stereo-model. Thus both the Leica/Helava and Intergraph DPWs have employed the VITec graphics processor for these purposes, while the latest Intergraph TDZ workstation with dual or quad Pentium Pro processors feature Intergraph's own GLZ graphics accelerator. All of 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 of the early prototype DPWs built by university groups featured digital signal processors or array processors to speed up computationally intensive tasks such as 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 appears to have disappeared from the market recently.

4.2 Data Display and Measurement

The use of a high-resolution display monitor is obligatory for a DPW, with 1,024 x 1,024 pixels = 1 megapixel being a minimum resolution to display image data on the screen. When displaying an image with 10μm pixel size at full resolution on such a monitor, it should be realised that this only displays an area of 1cm x 1cm from an aerial photograph having a standard format of 23cm x 23cm. The use of a two-megapixel, 27 inch (68.5cm) wide display monitor by Intergraph (Kaiser 1990) is quite exceptional; so far, this has not been adopted by other system suppliers. Associated with the requirement for high resolution is the need for high refresh rates of the monitor screen - typically 100 or 120Hz - especially if the left and right images needed for stereo-viewing have to be alternated on the screen at 50 to 60Hz to obviate flickering in the stereo-model. Frequently DPWs are supplied with two monitors - the one used for the image display, the other for the display of the system information, commands, prompts, etc.

The measuring mark (or cursor) is formed through the use of a cluster of pixels to form a cross or a circular mark. This is moved around the image by the operator using some type of control device such as a mouse, trackerball, tablet or hand wheels to apply the required screen pixel increments. The required movements can be implemented in one of two ways - either having a fixed cursor with a moving image (as used in analogue and analytical stereo-plotters) or having a fixed image and a moving cursor. The latter is much easier to implement; the alternative of a continuous movement of the image and its graphics overlay in a stereo-model against a fixed cursor is a computationally and memory intensive operation. Sub-pixel movement of the measuring mark is obtained by magnifying (i.e. zooming) the image but not the cursor.

4.3 Stereo-Viewing

The provision of this facility is regarded by most photogrammetrists as being an absolute necessity both for the measurements of the ground control points needed for absolute orientation and for the subsequent measurement of the detail (now called feature extraction!) required for topographic map compilation and the 3-D digital data needed for use in a GIS/LIS environment (Sarjakoski and Lammi 1992). It is also a vital element in carrying out map revision and the editing of the digital elevation data produced by automatic image matching techniques. Last, but not least, it also permits the stereo-superimposition of vector data over the stereo-model for checks of accuracy and completeness. Thus virtually all DPWs feature a stereo-viewing and measuring capability - except for one or two systems emanating 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; others are possible - see Petrie (1984) for some of these possibilities.

(a) The first possibility is to utilize 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 (Fig. 8). Alternatively the two monitors can be set at right angles to each other, the one with its axis pointing horizontally, the other pointing vertically upwards. One has a horizontal polarization sheet placed in front of it; the other has a vertical polarization sheet. A large semi-reflecting mirror set between the two monitors acts as a beam splitter. This allows the two component images to be superimposed on each other, while the operator wears appropriate spectacles with horizontally and vertically polarizing filters to allow stereo-viewing (Fig. 9). This arrangement was used by Matra in its Traster analytical plotters employing hard-copy photographs. Now the same basic arrangement is being used in both the Topcon PI-1000 and the recently introduced Galileo/Siscam Stereodigit and Microdigit DPWs (Capanni and Flamigni 1996). 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 possibility of flickering. The Microdigit utilises twin liquid crystal displays; however all the other DPWs in this group utilize conventional CRT-based monitors.

(b) 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 (Fig. 10) - the so-called split-screen stereo method. This was the method used in the pioneering Kern DSP1 and it is currently in use both on the DVP, marketed by Leica (Gagnon et al 1995), as well as on Leica's own 600 series DPWs. GeoSystems' Delta Workstation is another DPW employing this arrangement (Malov et al 1996).

(c) A low-cost solution is to simply superimpose the two component images of the stereo-pair on the screen of a single colour monitor with the one image displayed in red and the other in blue using the well-known anaglyphic technique familiar to photogrammetrists from early analogue stereo-plotting instruments such as the Multiplex, Balplex, Kelsh Plotter, etc. based on optical projection. Users view the resulting stereo-model appearing on the monitor wearing spectacles with the corresponding red/blue filters (Fig. 11). This method is used in the R-WEL DMS

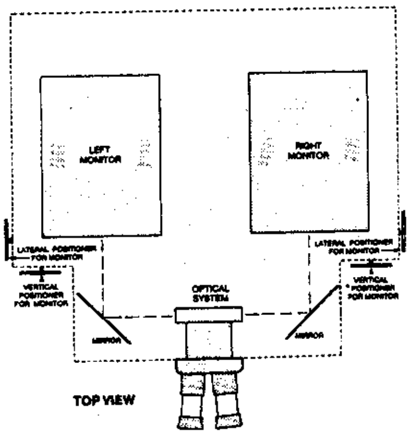


Fig. 8 - Twin Monitors Viewed with a Mirror Stereoscope.

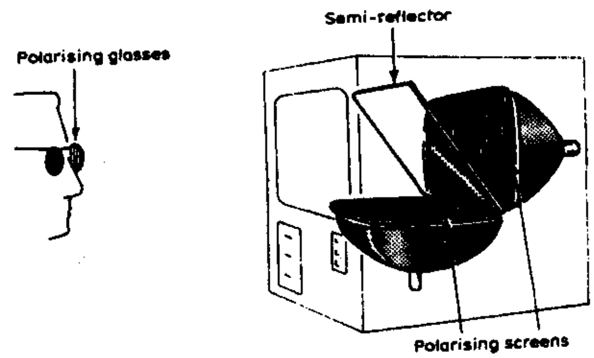


Fig. 9 - Twin Monitors Viewed with Polarizing Spectacles.

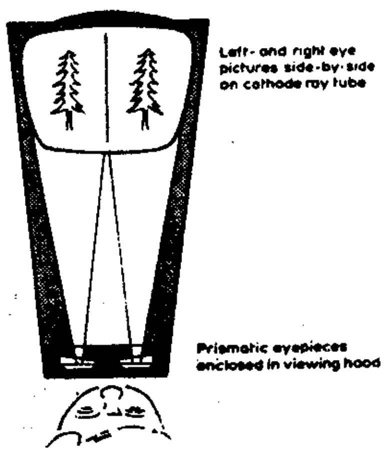


Fig. 10 - Single Monitor with Split-screen Viewing.

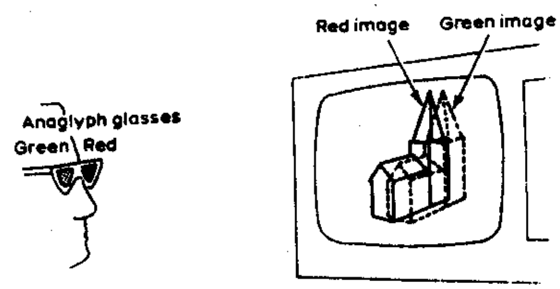


Fig. 11 - Stereo-viewing with Anaglyphic Spectacles.

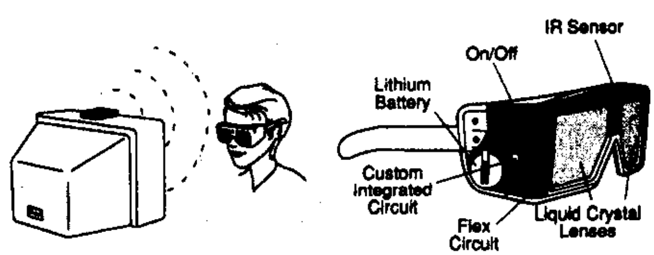


Fig. 12 - Alternating Images on the Monitor Screen with Alternating Shutters for Stereo-viewing.

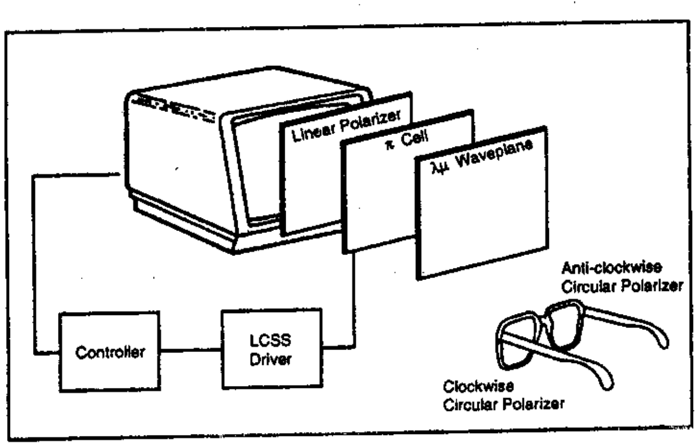


Fig. 13 - Alternating Images on the Monitor Screen with an Electronic Prism in Front of the Screen and Stereo-viewing Utilizing Polarizing Spectacles.

system (Welch 1987) and in some of the systems such as TNT-MIPS originating from remote sensing system suppliers. Obviously it is limited to the use of monochrome (black and white) imagery.

(d) A commonly used stereo-viewing system on DPWs is to display the left and right component images alternating on a single monitor screen at high speed, e.g. 50 to 60 Hz per image. The viewing is carried out using spectacles equipped with alternating shutters which are synchronised with the images being displayed on the monitor so that the left eye sees the left image only and the right eye the right image only (Fig. 12). Again the basic idea is familiar to those photogrammetrists who have used systems such as the Stereo-Image Alternator (SIA) on older optical projection instruments such as the Balplex and Kelsh Plotter. However these used mechanical shutters; those in use with DPWs use electronic PZLT or LCD alternating shutters which are synchronized with the display image either by direct wiring to the display controller or using an infra-red emitter mounted on top of the monitor. Most of the DPWs utilizing this technology have adopted the CrystalEyes system from the StereoGraphics Corporation based on the use of liquid crystal shutters and an infra-red emitter; however cheaper alternatives can now be sourced from suppliers in the Far East. The system is now in widespread use by Zeiss, Intergraph, VirtuoZo, Autometric/ERDAS, and as an option by Leica for its DPW 700 series. It is noticeable that the method is mainly in use on those DPWs based on SGI graphics work stations which are "stereo-ready", i.e. they do not need additional hardware to implement the method.

(e) The final method also uses alternating (left/right) corresponding images displayed on a single monitor screen. However, in this case, each image has a different polarisation pattern (clockwise/anti-clockwise) induced by an electronic prism mounted in front of the display monitor (Fig. 13). Users viewing the stereo-model wear spectacles equipped with the corresponding polarising filters - these are described as being "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 these DPWs driven by a Sun SparcStation, e.g. those supplied by Leica, Matra and DAT/EM.

It will also be noted that almost all of these stereo-viewing systems allow a number of users to view the stereo-images simultaneously. Only those systems employing mirror stereoscopes restrict the viewing to a single observer, though doubtless, if required, this restriction could be overcome through the use of dual oculars as was done with a number of analogue stereo-plotting instruments.

4.4 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 to execute the various mensuration tasks that have to be carried out on a DPW. These tasks include the measurement of well-defined points such as fiducial marks, ground control points, etc. in a static mode and the continuous stereo-plotting 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 that were developed originally for analytical plotters (Petrie 1992), e.g. the P-cursor used by Zeiss, Intergraph's multi-button cursor (Fig. 14); and the Wild BC measuring device. Similar controlling/measuring devices have been developed for DPWs by Autometric, DAT/EM, etc., while Matra utilizes the tracker ball (for planimetry) and thumb-wheel (for height) arrangement previously used in its Traster analytical plotters (Cruette 1991). A number of system suppliers also offer hand-wheels and foot-disks for high precision pointing and plotting as used in traditional analogue and analytical stereo-plotters (Fig. 15).

Fig. 13 - Intergraph InterMap Digital (IMD) Stereoplotter based on the Intergraph IP 6487 or 6887 ImageStation and featuring a 27 inch, 2 Megapixel colour screen; a two-handed measuring cursor and the CrystalEyes stereo-viewing system with "active" spectacles.

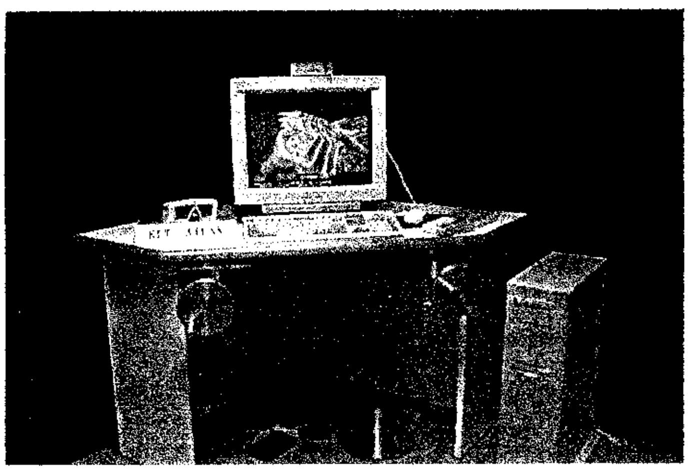


Fig. 15 - KLT Associates Atlas/DSP digital photogrammetric workstation based on the use of a PC running MS-DOS and equipped with handwheels, a footdisk, footpedals and a function keypad. Stereo-viewing can be carried out using either the CrystalEyes or Tektronix systems with alternating images or a split-screen viewing system.

Fig. 16 - Leica/Helava DPW 770 based on the use of a Sun SparcStation running two monitors, one for stereo-viewing, the other used for the display of system information, commands, etc. Stereo-viewing is carried out using the Tektronix system with "passive" polarizing spectacles and measurement using a tracker ball.

Some of the 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 measuring mark would be a complete understatement - at least in the opinion of the present author! Indeed, often the ergonomics and working environment of many current DPWs fall a considerable way behind those provided by analytical plotters.

5. Classification of DPWs

The integration of all the individual hardware elements discussed in Section 4 above in different combinations to form a DPW has resulted in a large variety of systems with differing capabilities and a wide range of costs being offered on the market. For convenience, these systems have been divided into three main categories as follows:-

(A) The first category comprises those DPWs which are based on powerful, high-specification, RISC-based graphics workstations running under the Unix operating system and the X-windows Graphical User Interface (GUI); and utilizing the more elaborate and expensive types of stereo-viewing and purpose-built controlling/measuring devices. Needless to say, these systems tend to come at the upper end of the price range of DPW systems. Apart from VirtuoZo, which is based on developments carried out at Wuhan Technical University of Surveying & Mapping (WTUSM) in China (Zhang, Zhang, Shen and Wang 1996) and is now being marketed, distributed and supported by an Australian company, all of the system suppliers have been or are suppliers of analytical plotters utilizing hard-copy images, including Leica/Helava, Intergraph, Zeiss, Matra, Autometric, and DAT/EM.

(B) Those systems which run on PCs under DOS and/or Windows form the second category. They are usually available at a substantially lower cost than those available from the mainstream suppliers falling in category (A). Three of these - Galileo/Siscam, Topcon and GeoSystems - are smaller but still active suppliers of analytical plotters, while ISM and KLT Associates are mapping consultants that previously have been producing conversion kits and software respectively for computer-based analogue and analytical plotters. Two of the other suppliers - DVP Geomatics and R-WEL - are spin off companies from universities (Laval and Georgia respectively), which have well known teaching and research programmes in the mapping sciences.

(C) The third group of DPWs are those which have been produced by certain of the major remote sensing system suppliers - ERDAS, PCI and MicroImages - usually with an emphasis on DEM and ortho-image production, both from aerial photography and SPOT stereo-imagery. So far, these DPWs have not been optimised 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.

Table II summarizes the currently available systems under the above classification.

6. Algorithmic and Software Aspects of DPWs

In purely algorithmic terms, the photogrammetric solutions used in the DPWs are basically the same as those employed in analytical plotters using the object coordinates primary solution (Fig. 16). They use the same basis of projective geometry and the same mathematical models, e.g. the collinearity and coplanarity solutions used to implement standard analytical photogrammetric procedures are those used in DPWs. Thus the inputs to the system from the operator's measuring device are X,Y,Z object coordinates and the DPW's real-time program generates as output the corresponding x,y positions of the measuring mark or cursor in pixel coordinates on each of the two images of the stereo-pair using standard collinearity equations.

(a) **Category A** (Based on Graphics Workstations running under UNIX OS)

	Autometric Soft-Plotter	DAT/EM Digitus	Helava 750/770	Intergraph IMD	Matra Traster T10	VirtuoZo	Zeiss Phodis ST
Computer	Silicon Gr.	Sun Sparc	Sun Sparc	Inter 6000	Sun Sparc	Silicon Gr.	Silicon Gr.
S. Viewing	Alt. Shutters	Polarising F.	Polarising F.	Alt. Shutters	Polarising F.	Alt. Shutters	Alt. Shutters
Measure	3-D cursor	3-D cursor	Trackball	3-D cursor	Trackball	Mouse	3-D cursor

(b) **Category B** (Based on PCs running DOS and/or Windows)

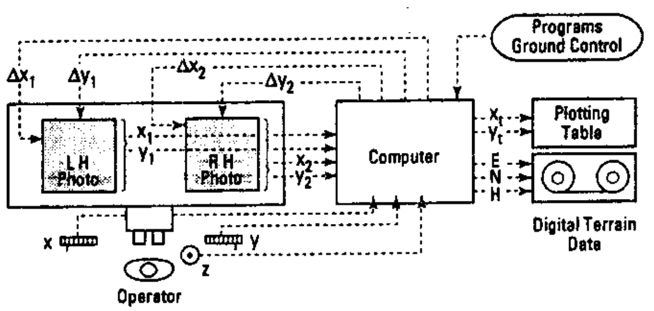
	Galileo/Siscam Microdigit	Galileo/Siscam Stereodigit	GeoSystem Delta W.S.	ISM DiAP	KLT Atlas/DSP	Leica DVP
S. Viewing	Twin LCD	Twin Monitor	Split Screen	Alt. Shutters	Alt.Shutters	Split Screen
Measure	Mouse	Mouse	H/F wheels	3-D cursor	H/F wheels	Dig. Tablet

	R-Wel DMS	Topcon PI-1000
S. Viewing	Anaglyph	Twin Monitors
Measure	Mouse	Mouse

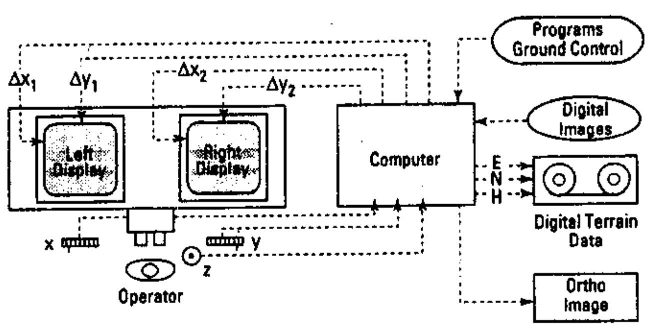
(c) **Category C** (Remote Sensing System Suppliers)

	ERDAS OrthoMAX	MicroImages TNT-MIPS	PCI EASI/PACE
Computer	Sun/SGI	PC	Sun/SGI/PC
S. Viewing	Alt.Shutters	Anaglyph	None
Measure	Mouse	Mouse	Mouse

Table II - Digital Photogrammetric Workstations with Full Stereo-viewing.



Analytical Plotter with Object Coordinates Primary



Digital Photogrammetric Workstation

Fig. 16 - The algorithmic aspects of the DPW are similar to those of an Analytical Plotter with object coordinates primary, since their basic system concepts are in principle the same.

While all DPWs must be able to handle aerial photography, quite a number are also designed to handle satellite imagery, mainly, at present, 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 will be generated both by the MOMS-02 and OPS missions and by the forthcoming American high-resolution commercial satellites such as Space Imaging, Early Bird and OrbView.

6.1 Orientation Software

Orientation procedures to form a stereo-model and to fit it to the ground control points and so bring it into the required map projection system are of course just as obligatory in a DPW as in analogue and analytical stereo-plotting instruments. Thus inner orientation via the measurement of the fiducial marks is a standard preliminary operation. Often in a DPW, this requires the first one or two such marks 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 cameras is now available from some DPW suppliers, e.g. for Autometric's SoftPlotter (Lue 1996).

Exterior orientation procedures may vary. Some systems employ 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 end 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 (Heipke 1996). However absolute orientation almost always requires operator interaction for identification of the ground control points.

The intrusion of some suppliers with no previous photogrammetric background can be seen when the measurement of ground control points for absolute orientation can only be made either through monocular measurements on each of the images making up the stereo-pair or by monocular pointing on the 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 3-D or using them to check the accuracy of pointing have either been overlooked or discarded. The impression of a comparative lack of knowledge or experience is reinforced when, on some systems, the results of the fit of the stereo-model to the ground control points (i.e. the absolute orientation) are only declared 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.

6.2 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 carried out on a model-by-model basis along the strip. Again image matching capabilities may be provided, often using an area-based or feature-based matching procedure utilizing an image pyramid with the correlation being carried out at successive image levels until the finest level is reached at which the image digitization has taken place. The use of such procedures is certainly more effective with fiducial marks, signalized points and well defined features than with less well-defined natural points; for the latter, a manual stereoscopic measuring capability is still required, more especially in featureless areas. 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 (Miller, Padares and Walker 1996).

Once the measurement phase has been completed, the actual software that is 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 can utilize 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 centres and the image rotations and translations can then be produced as headers for each of the digitized images to assist in the setting up of individual stereo-models for subsequent map compilation and DEM and ortho-image production.

6.3 Map Compilation Software

Here again, the tendency is to incorporate into the DPW well-established third-party software packages that have been developed originally for use on analogue and analytical stereo-plotting instruments to carry out the acquisition of photogrammetric data (feature extraction) for input to digital mapping, CAD and GIS systems. Typical of these packages are ATLAS from KLT Associates; KDMS from Kork Systems (now part of the Autometric/Vision International group); DWG and DGN/CAPTURE from DAT/EM; Pro 600 from Leica; CADMAP (now owned by Zeiss); etc. All of these packages also 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 the structuring and editing of photogrammetrically captured vector data. Once this has been completed, the transfer of the structured and edited data to the digital mapping, CAD or GIS/LIS system takes place using a standard protocol such as DXF.

So far, there has been little sign of automatic feature extraction reaching production status in spite of the intensive research work that has been 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. Thus operator interaction with the system is still obligatory if point features and vector line data are to be extracted for digital map production or input to a CAD or GIS/LIS system.

6.4 Software for DEM Production

There is little doubt that the automatic generation of digital elevation model (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 a number of products - e.g. Zeiss Phodis TS (for DEMs) and OP (for digital orthophotos); Galileo/Siscam Orthomap; Inpho Match-T (for DEMs); etc. - that are simply dedicated to these tasks and are available and sold as stand-alone systems to carry out these operations. Thus they do not posses the full functionality of a DPW, so carrying a much lower price-tag than that required for a full-blown DPW system.

It should go virtually without saying to experienced photogrammetrists that failure cases must occur to at least some extent during all automatic DEM and ortho-imaging operations. In areas containing few well-defined features, and exhibiting a lack of 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 the occluded/dead areas and height discontinuities arising from the presence of high buildings and forests in the areas being mapped. Thus the key to the successful implementation of 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 for 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. However the fact is that certain packages used in DPWs, for example some of those provided by remote sensing system suppliers, do not provide such facilities. In which case, the required editing is problematic to say the least and virtually impossible in some situations - as the present author can testify rather feelingly!

Apart from the automatic image matching technique, some DPWs are also provided with software giving the capability of driving the measuring mark 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 (Petrie 1990). The elevation measurements can then be carried out either by image matching (where suitable conditions apply) or manually in stereo by an operator. The latter will then supplement these measurements through selective sampling via the measurement of breaklines and other important topographic features to provide a more complete DEM on the basis of a composite sampling strategy. Needless to say, the provision of an interface and data transfer facilities to connect the DPW to well-established digital terrain model (DTM) systems which can provide contouring, cross-sections, profiles and perspective views based on the DEM data should be obligatory, but sometimes these are not provided.

6.5 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 GIS/LIS systems on which existing vector data can easily be superimposed. It is also possible to carry out the vector digitizing of the features contained in the orthophotographs through "head-up" digitizing on-screen, either for map revision purposes or for input to the GIS/LIS system.

A notable feature of some DPW orthophoto software modules is that of being able to carry out mosaicing 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, while the most sophisticated may even attempt geometric and radiometric feathering of the adjacent images to provide a seamless final composite image. Not infrequently, however, this time-consuming mosaicing procedure will be carried out off-line on a dedicated editing station rather than on the DPW being used for the data acquisition. Furthermore many users supplement the image processing routines included in the package provided by the system supplier with those provided by a general-purpose package such as Adobe Photoshop. Finally it is worth noting that corrections for building lean, i.e. roof correction software, for use in the production of orthophotographs at large scales in urban areas is a recent innovation from Leica/Helava.

7. Output from a DPS

Since this paper aims to discuss the whole digital photogrammetric system and the input side has already ben discussed, including some detailed consideration of scanners, it appears logical and consistent to include some discussion of 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 or coordinatograph such as the Wild Aviotab and Zeiss Planitab based on the use of vector data 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 of these devices can be attached either directly to the DPW or, more commonly nowadays, they are accessed over a network via a plot server, thus providing a resource that can be shared by a number of DPWs or analytical plotters.

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

The principal available devices can be grouped conveniently under the following headings:-

(i) electrostatic plotters; (ii) inkjet plotters; (iii) thermal plotters;
(iv) laser plotters; and (iv) film plotters.

7.1 <u>Electrostatic Plotters</u>

This is a relatively mature and well developed technology which is available to handle large formats - up to 36 inches (90cm) and 44 inches (120cm) in width with effectively no limitations in length. - and generate map images at moderate resolutions (300 dpi), either in monochrome or in colour. These come 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 the generation of colour hard copy both on film and on paper. The purchase price of these devices is relatively high, but visits to mapping agencies confirm that they continue to be used for the generation of edit plots and colour proofs and those map products which are required in small numbers (i.e. requiring short runs) for reports.

7.2 <u>Inkjet Plotters</u>

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

(i) the <u>drop-on-demand type</u> in which tiny particles of ink are ejected through a nozzle on to paper or film through the action of a piezo-electric crystal;
(ii) the <u>bubble jet type</u>, in which tiny heating elements are incorporated in the nozzle and some of the ink is volatilised and forms a gas bubble which again ejects an ink droplet on to the plotting medium; and
(iii) the <u>solid inkjet</u> (or phase change) <u>device</u> which utilizes solid ink sticks which are melted by heating prior to the ejection of the ink droplets.

These devices compete successfully against the other types of small-format colour plotters (thermal wax and laser) mentioned above, especially given their lower purchase cost.

However the <u>larger-format inkjet plotters</u> are those of most interest to mapping organisations. A monochrome version that has come into widespread use is the Hewlett Packard DesignJet which can accommodate either cut sheets or 24 inch (60cm) or 36 inch (90cm) 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 of these devices have become very popular in mapping agencies; indeed one can say that their comparatively low purchase price and reasonable performance is fast making them the dominant plotter technology at low to medium resolutions, capable of producing an acceptable quality of image map as well as vector line maps.

At the top end of the price and quality scale range are the inkjet plotters produced by <u>Iris Graphics</u> in a variety of format sizes - 10.6 x 17 inch (27 x 44cm); 24 x 24 inch (60 x 60cm); and 34 x 44 inch (84 x 112cm). These utilize a sophisticated type of inkjet technology combining variable dot size and dithering to achieve excellent quality either on film or on paper (Fig. 18). Needless to say, the Iris products cost considerably more than the DesignJet or Novajet devices, but the extra cost is justified if very high quality is required, e.g. with image maps.

7.3 <u>Thermal Plotters</u>

These plotters, available for example from 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 in monochrome only at reasonable resolutions (400 dpi). More recently, bicolour media have been introduced allowing the generation of both black and red colours, which can be a most useful feature, e.g. for showing up revision detail on large-scale maps.

	Light Source	Wave-length	Safe-light	Max. Film Size
Agfa SelectSet 36/44	Laser Diode	650nm	Cyan	36 inch (90cm)rolls
Barco BG 3800	HeNe Laser	633nm	Cyan	31x43 inches (80x110cm)
Barco MegaSetter	HeNe Laser	633nm	Cyan	47x63 inches (120x161cm)
Intergraph Mapsetter 6000	Argon Laser	488nm	Yellow	47 inch (120cm) rolls
Intergraph Optronics 5040	Argon Laser	488nm	Yellow	41 inch (104cm) rolls
Escher Grad EG 8000/9000	Laser Diode	635nm	Cyan	30/50 inch (75/127cm) rolls
Lüscher 2012	LED Array	660nm	Cyan	48 inch (122cm) rolls

Table III - High Quality Raster Film Plotters

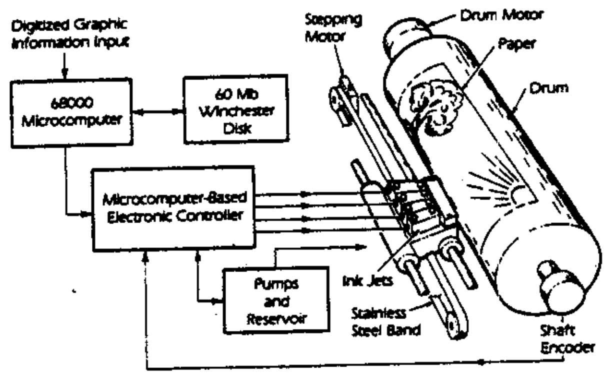


Fig. 18 - Iris Graphics Large-format Inkjet Plotter.

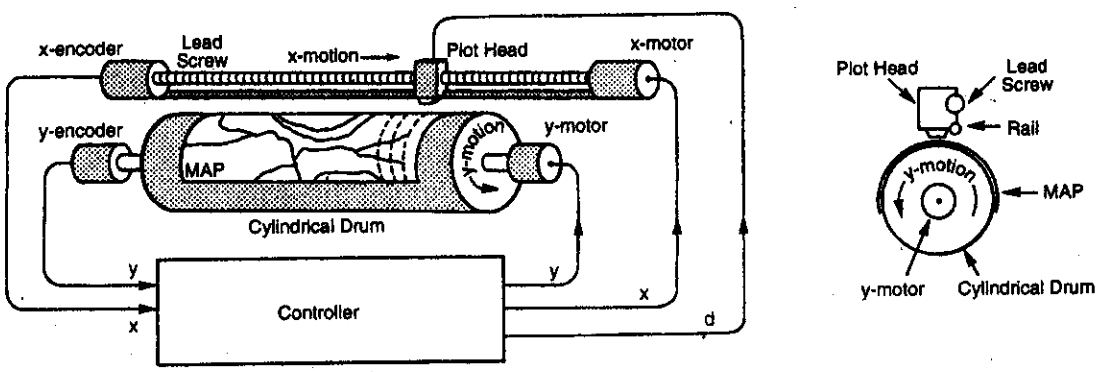


Fig. 19 - Large-format Rotary Drum Plotter.

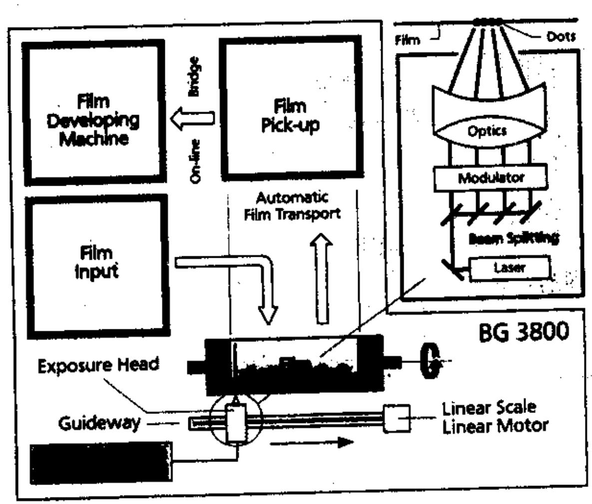


Fig. 20 - System Concept of Barco BG 3800 Raster Film Plotter.

7.4 Laser Plotters

Besides the small-format colour laser plotters mentioned above in the introduction to Section 7, there also exist 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, though they tend to be less widespread because of higher cost.

7.5 Film Plotters

Since currently the DPW is much used for the generation of orthophotographs and ortho-images, so the matter of utilizing film plotters that can retain fully 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 (Fig. 19). Typical are those sold by Kodak, SEP and Intergraph/Optronics and the Macdonald Detwiler/Cymbolic Sciences Fire series. These only allow a limited format size to be produced - typically 10 x 12 inch (25 x 30cm) - but at high resolutions, e.g. 2,500 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 such as Barco's MegaSetter and BG-3800 (Fig. 20), the Agfa SelectSet and 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. A summary of the range of these devices currently available on the market together with their main characteristics is given in Table III. These plotters can produce the very high resolution (up to 4,000 dpi) stable film negatives or positives required for use as colour separations for the production of the printing plates needed for the colour printing of maps and image maps using offset litho techniques. In fact, the new Barco LithoSetter even allows the direct production of printing plates from the digital image data. Notwithstanding the large investment needed to acquire such devices, it is extremely instructive to note how prevalent these film plotters have become in the West European national mapping agencies - in Great Britain, Ireland, Norway, Sweden, the Netherlands and Austria - visited recently by the present author.

Associated with these developments is the use of very powerful raster image processors (RIPs) to convert the image data to the appropriate raster format required by the plotter. Various strategies have been adopted, including purely software-based solutions carried out on plot servers, but most film large-format plotters appear to incorporate dedicated processors and hardware to carry out this demanding and computationally intensive task in the shortest possible time to improve throughput.

8. Conclusion

As the account given above has shown, the digital photogrammetric system has come of age with the introduction of a great variety of products and approaches by a large number of suppliers from which mapping agencies can make the choice that best suits their particular requirements. There are still many existing analogue photogrammetric instruments in operation world wide and analytical plotters are still selling in substantial numbers, but undoubtedly the way ahead lies with the all-digital instrumentation. However considerable development is still required both to bring down costs of ownership which, at present, seem to be unduly high, and to ensure the adoption of the DPW for map compilation/feature extraction to complement its present successful role which is largely concentrated on the generation of DEMs and ortho-images.

With regard to developing countries, e.g. those in Africa, it has been tragic and frustrating to observe that they have missed out almost completely on gaining access to the previous and current generation of photogrammetric instruments, the analytical plotters. It remains to be seen whether the situation will be any different with the new digital systems. A hopeful aspect is that, in certain respects, they are much simpler in terms of their hardware. Thus the high-class optical and mechanical components of the analogue and analytical instrumentation which need regular maintenance and repair by skilled specialists from the system suppliers have been greatly reduced or eliminated. But still there is a need for a good infrastructure, both in terms of local technical support for computer systems as well as more basic requirements such as a reliable electricity supply.

With regard to the level of expertise necessary to make good use of the DPS, it is possible to discern two quite differing opinions or viewpoints. The first is that the advent of the DPS and the automated tools associated with it has improved the ease of use of photogrammetric systems substantially and so reduced the degree of expertise needed to utilize such systems in an efficient manner within both the mapping and GIS/LIS environments. The other view is that the eternal verities of photogrammetry will continue to apply and that the increased sophistication of the systems will continue to demand a high level of knowledge and expertise on the part of users if these systems are to be deployed in an efficient and cost-effective way. It will be interesting to see which of these viewpoints is proven to be correct in the long run. In the meantime, the advent of the DPS has ensured that photogrammetry retains its endless fascination for those fortunate enough to be involved in it.

ACKNOWLEDGEMENTS

The author wishes to express his grateful thanks to Stewart Walker (Leica/Helava), Rob van Westenberg (KLT Associates) and Derek Ireson (Intergraph) for the supply of the illustrations of workstations and scanners contained in this paper. As ever, he is also indebted to his technician colleagues, Mike Shand and Ian Gerrard, for their excellent work in producing the many diagrams contained in this paper.

REFERENCES

Armenakis, C., Regan, A.M. and Dow, A., 1996 - Softcopy Photogrammetric Applications for National Topographic Mapping. Geomatica, Vol. 49, No. 4: 433-443.

Capanni, G. and Flamigni, F., 1996 - SISCAM Softcopy Photogrammetric Workstation. International Archives of Photogrammetry & Remote Sensing, Vol. 31, Part B2, 41-45.

Colomer, J.L. and Colomina, I., 1994 - Digital Photogrammetry at the Institut Cartographic de Catalunya. Photogrammetric Record, Vol. 14, No. 85: 943-956.

Cruette, C., 1990 - Design and Development of the Matra Traster T10. Digital Photogrammetric Workstations (Eds. H. Ebner, D. Fritsch and C. Heipke), Wichmann, Karlsruhe, Germany: 167-176.

Gagnon, P-A, Boulianne, M., Agnard, J-P., Nolette, C. and Coulombe, J., 1995 - Present Status of the DVP System. Geomatica, Vol. 49, No. 4: 479-487.

Heipke, C., 1995 - State-of-the-Art of Digital Photogrammetric Workstations for Topographic Applications. Photogrammetric Engineering & Remote Sensing, Vol. 61, No. 1: 49-56.

Heipke, C., 1996 - Automation of Interior, Relative and Absolute Orientation. International Archives of Photogrammetry & Remote Sensing, Vol. 31, Part B3: 297-311.

Johansson, M., Miller, S.B. and Walker, A.S., 1995 - Digital Orthophotography at the National Land Survey of Sweden. Proceedings, GIS/LIS 95, Vol. 1: 522-529.

Kaiser, D., 1990 - ImageStation : Intergraph's Digital Photogrammetric Workstation. Digital Photogrammetric Workstations (Eds. H. Ebner, D. Fritsch and C. Heipke), Wichmann, Karlsruhe, Germany: 188-197.

Kirwan, R.A., Miller, S.B. and Walker, A.S., 1996 - Successful Digital Photogrammetry at the Ordnance Survey of Ireland. International Archives of Photogrammetry & Remote Sensing, Vol. 31, Part B4: 925-930.

Leberl, F.W., Best, M, and Meyer, D.,1992 - Photogrammetric Scanning with a Square Array CCD Camera. International Archives of Photogrammetry & Remote Sensing, Vol.29, Part B2: 358-363.

Lue, Y., 1996 - Towards a Higher Level of Automation for SoftPlotter. International Archives of Photogrammetry & Remote Sensing, Vol. 31, Part B3, 478-483.

Malov, V., Oleynik, S., Gajda, V. and Zotov, G., 1996 - Digital Photogrammetric Station "Delta". International Archives of Photogrammetry & Remote Sensing, Vol. 31, Part B2: 238-243.

Miller, S.B., Padares, F.C. and Walker, A.S., 1996 - Automation in Digital Photogrammetric Systems. International Archives of Photogrammetry & Remote Sensing, Vol. 31, Part B3: 250-255.

Miller, S.B., Walker, A.S. and Walsh, M.C., 1995 - Digital Photogrammetry at the Ordnance Survey of Ireland, Technical Papers, ASPRS-ACSM Annual Convention and Exposition, Vol. 2: 195-204.

Petrie, G., 1984 - The Philosophy of Digital and Analytical Photogrammetric Systems. Proceedings of the 39th Photogrammetric Week, Special Publication No. 9, Institute for Photogrammetry, University of Stuttgart: 53-68.

Petrie, G., 1990 - The Impact of Analytical Photogrammetric Instrumentation on DTM Data Acquisition and Processing. Terrain Modelling in Surveying and Civil Engineering (Eds. G. Petrie & T.J.M. Kennie), Whittles Publishing, Caithness, U.K.: 49-72.

Petrie, G., 1992 - Trends in Analytical Instrumentation. ITC Journal, 1992-4: 364-382.

Sarjakoski, T. and Lammi, J., 1992 - Requirements of a Stereo Workstation for GIS Environment. International Archives of Photogrammetry & Remote Sensing, Vol. 29, Part B2: 266-274.

Walker, A.S. and Petrie, G., 1996 - Digital Photogrammetric Workstations, 1992-96. International Archives of Photogrammetry & Remote Sensing, Vol. 31, Part B2: 384-395.

Welch, R., 1987 - Desktop Mapping with Personal Computers. Photogrammetric Engineering & Remote Sensing, Vol. 55, No. 11: 1651-1662.

Welch, R., 1993 - Low-Cost Softcopy Photogrammetry. Geodetical Info Magazine, Vol. 7, No. 12: 55-57.

Zhang, J., Zhang, Z., Shen, W. and Wang, Z., 1996 - VirtuoZo Digital Photogrammetry System and its Theoretical Foundation and Key Algorithms. International Archives of Photogrammetry & Remote Sensing, Vol. 31, Part B2: 424-429.