# DIGITAL PHOTOGRAMMETRIC WORKSTATIONS 1992-96

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Invited paper, Intercommission Working Group II/III

**KEY WORDS:** Digital Photogrammetric Workstations, Softcopy, Systems, Hardware, Software, Automation, Status.

## ABSTRACT

Digital photogrammetric workstations are on the point of superseding analytical plotters, following a vigorous expansion of their use during the period 1992-96. An aggressively competitive market-place has developed, in which several manufacturers offer systems which perform the basic digital photogrammetric tasks - orientation, digital terrain models (DTMs), orthophotos, feature extraction - and in some cases include interesting additional functionality. The hardware platforms, operation and functionality of these systems are all improving apace, while certain developments of the software represent radical innovations, especially automated triangulation, mosaics and semi-automated tools for feature extraction. Acclaim of this technical wizardry must be tempered with comment on customers' applications and expectations. Intriguing too is the ongoing debate whether digital photogrammetry is evolutionary or revolutionary and to what extent the promise of digital photogrammetry has been fulfilled in terms of the use of automation. While DPWs have an assured future and their accession to the role of workhorse in photogrammetric production is imminent, their perceived technical pre-eminence is conditional upon greater automation leading to unarguable increases in productivity and operator comfort, coupled with users finding markets for the much wider range of deliverables which digital photogrammetry can generate *vis a vis* analogue or analytical.

## 1. INTRODUCTION TO DIGITAL PHOTOGRAMMETRIC SYSTEMS

By 1992 digital photogrammetric workstations (DPWs) had begun their migration from military applications into the commercial market-place. This had taken ten years. Four years later their status is equal to, perhaps greater than, the analytical plotter (AP). They have not quite superseded analytical plotters, but almost so. Yet a DPW is not an AP: it performs the functions of an AP, but many more tasks besides. Why then the frequent comparisons with APs?

By adopting digital methods, photogrammetry accepted its third "paradigm" and the change from analytical to digital is proving shorter and sharper than from analogue to analytical some 15 to 20 years ago (Leberl, 1991, 1992a). The huge growth of the DPW literature is informative: before the 1992 Congress there were overview papers offering analyses, taxonomies and predictions, for example by Dowman (1991a, 1991b), Dowman *et al.* (1992) and Schenk and Toth (1992); and there were product descriptions by vendors, for example Helava (1991a), lifting the wraps off previously less well known military systems, Kaiser (1991) and Nolette *et al.* (1992). Overviews were given at the last Congress, for example by Leberl (1992b) and are still written, both more penetrating academic analyses, for example Leberl (1994) and Heipke (1995a), and lighter pieces designed to bring appreciation of the technology to wider audiences, for example Trinder and Donnelly (1996). Vendors, too, continue to write updates on their latest product lines, for example Dörstel (1995), Miller and Walker (1995) and Gagnon *et al.* (1995). Users have found their pens in droves, spurred by a desire to explain how they have encompassed the new technology, for example Corbley (1995), Foley *et al.* (1993), Johansson *et al.* (1995), and Kirwan (1996). Some go further and compare systems, for example Baltsavias *et al.* (1996) and Kölbl (1996). The whole field has been surveyed by Heipke (1995b). Here we set DPWs within the overall digital photogrammetric process, then discuss the hardware and software, attempting to discern trends where appropriate. We briefly compare DPWs and APs from the user's standpoint and assess how great an achievement the current status of DPWs may be.

### 1.1 Basic components

Digital photogrammetric systems have become well understood. The major characteristics are:

(i) the system combines computer hardware and software to allow photogrammetric operations to be carried out on digital image data;
(ii) the sets of digital image data consist of arrays of picture elements (pixels) of fixed size and shape; each pixel has one or more brightness values giving the value(s) of the radiance from the object field falling on each individual element of the imaging sensor;
(iii) the sensor may produce digital data, for example a digital camera incorporating an areal array of CCDs, or a pushbroom scanner with a linear array of CCDs;
(iv) data is often derived from a camera producing frame images on photographic film; these are converted into digital form using high precision scanners;
(v) the main element of the system is the DPW on which the required mathematically based photogrammetric operations are carried out to produce data for input to digital mapping, CAD or GIS/LIS systems;
(vi) these operations are performed manually or interactively, for example most feature extraction and editing, or using automated or semi-automated methods, for example DTMs and orthophotos;
(vii) final output may take the form of vector line maps, DTM data files or image maps; thus many systems include raster plotters or film writers.

### 1.2 Input data

**1.2.1 Sensors.** The data volumes in digital photogrammetry are considerable, but vary according to the sensor. Digital cameras are rather seldom used in aerial photography as yet, but are quite common in close range applications. Formats of 2000 x 2000 pixels are still quite large: these would give 4 MB per image greyscale, 12 MB colour. Data volumes from remote sensing pushbroom scanners are larger, for example SPOT: 6000 x 6000 greyscale, i.e. 36 MB, or 3000 x 3000 colour, i.e. 27 MB. But by far the greatest source of imagery is film photography from aerial cameras with 23 x 23 cm format. This imagery must be scanned for input to digital photogrammetric systems. The latest cameras, of course, are equipped with forward motion compensation, stabilised mounts and on-board GPS; today's lenses tend to be available only in 15 and 30 cm sizes, have negligible distortions and permit practical lens/film resolutions up to 70 lp/mm.

**1.2.2 Scanners.** There is on the market-place a rich variety of photogrammetric scanners, which are capable of geometric accuracies similar to or just below those of APs, i.e. root mean square errors of 2-10 µm per axis. These can produce radiometrically satisfactory data in 8 or 10 bit greyscale or 24 bit colour at raw pixel sizes between 3 and around 20 µm in perhaps 3-15 minutes greyscale or 10 minutes to over one hour colour. The current trend is towards models which can handle negative roll film. Though the software must include sophisticated filtering to emulate traditional dodging, these new generation scanners offer considerable savings since diapositives are no longer required.

For users whose requirements are less stringent, especially those who purchase the entry level DPWs from companies like R-WEL and DVP and whose work may consist mainly of medium and small scale topographic mapping, several scanners from the desk top publishing world have been found useful These include the Agfa Horizon and Sharp JX-610, which can accommodate 23 x 23 cm format, unlike the more common A4 and letter size scanners, and scan both prints and diapositives. They give satisfactory results in the 20-50 µm range, though for some applications an attempt should be made to compensate for systematic geometric errors.

A system resolution of 60 lp/mm from an aerial camera is equivalent to around 8 µm. In theory a higher scanning resolution, perhaps 6 µm, is required to capture this, but users seem to have settled on values of 10-30 µm for all except intelligence applications. At 25 µm, a greyscale image occupies 81 MB, at 10 µm, about 0.5 GB. Since DPWs usually work on two or more images simultaneously, many images are colour and most systems require image pyramids and/or epipolar resampled images, the data volumes are daunting. Thus there has been strong support for image compression (see 2.2.1 below). Large, increasingly economical storage devices have alleviated matters too (section 2.2.2 below and for data transfers between scanners and DPWs, or from one DPW to another, the focus has shifted towards higher performance networking solutions (section 2.5 below).

### 1.3 History and early classifications

Though the ideas of digital photogrammetry date back to the 1950s and extensive work was done on topics like image matching in the 1960s and 1970s, many of the solutions were of a hybrid nature and it was late in the 1970s before the DPW as we understand it today was mooted (Sarjakoski, 1981). A milestone occurred when General Dynamics was awarded a contract by the Defense Mapping Agency (DMA) and recruited Helava Associates, Inc., as a sub-contractor. The result was the Digital Stereo Comparator Compiler (DSCC), an expensive workstation with custom built electronics and twin monitors viewed through optical trains (Case, 1982; Helava, 1991; Miller, Helava and Devenecia, 1992). Today, the successor company, GDE Systems, Inc., continues to supply military systems, albeit with an extensive commercial off the shelf (COTS) component, while its subsidiary, still called Helava, supplies systems to the commercial market through Leica.

During this period, numerous other vendors have joined the race. Two companies which were active in remote sensing and photogrammetry in the 1980s, ContextVision and I²S, are no longer competing, but the other vendors are most interesting. Leica was amenable to the cooperation with Helava because its preoccupation with both the Kern and Wild AP lines precluded the extensive development work essential to bring its pioneering DSP1 (Cogan *et al.*, 1988) to a competitive standard. The big photogrammetry vendors, Intergraph and Zeiss, are prominent, just as they were in analytical photogrammetry. Yet there is a contrast. Intergraph pulled out of analytical photogrammetry early on, content to compete with residual units of its Intermap Analytic AP (the IMA), developed under DMA contract, and preferring to move into the digital arena at the beginning of this decade with the PS1 scanner and the ImageStation InterMap Digital (IMD) DPW. The former had optics and mechanics built by Zeiss, as had had the IMA, whereas the latter was based on Intergraph's own Clipper proprietary Unix workstation with characteristic huge screen and two plane keyboard (Kaiser, 1991). Zeiss, perhaps handicapped by the amalgamation of the Oberkochen and Jena operations, made a more subdued entry, also with the PS1 but with its own PHODIS DPW (Dörstel (1995) gives a recent update).

Like General Dynamics, the US defence contractor Autometric, which had supplied a number of its Pixar-based Pegasus systems to the US military, wanted to enter the commercial market-place and formed a subsidiary to pursue this goal. This was Vision International, which soon purchased Kork, the Bangor, Maine, supplier of feature extraction software for stereoplotters, and made a close alliance with ERDAS, the leading remote sensing software vendor from Atlanta. ERDAS sells OrthoMAX, which is also offered as a component of Vision's more comprehensive system, SoftPlotter. Of the other AP suppliers, Matra was an early entrant with the T10, while Galileo SISCAM has turned to digital photogrammetry rather quietly, despite its ample expertise in the field, and OMI, Adam Technology and Qasco have chosen to wait and see. A more resolute effort has been made by software houses, especially producers of feature extraction software for analogue and analytical plotters, i.e. DAT/EM and KLT from the US and ISM from Canada. Vexcel has split into two companies: its scanner division offers a product for digital triangulation, IDAS, and its research division now has FotoG-FMS, a digital form of the well known close range package.

Three well known players have no pedigree as photogrammetric instrument suppliers, but all have strong university links. DVP Geomatics, Inc., is a company in a Quebec surveying company, which took on some educational software from Université Laval for commercial distribution. R-WEL, Inc., the company of Professor Roy Welch of the University of Georgia, Athens, had previously offered only a small software package for flight planning. Yet both these companies offer low cost PC based DPWs with surprising functionality and correspondingly broad customer bases (Nolette *et al.*, 1992; Gagnon *et al.*, 1995; Welch, 1989). The third, however, offers a fully fledged DPW with many innovative features: VirtuoZo offers a product developed by Wuhan Technical University for Surveying and Mapping and is competing worldwide.

Many vendors offer products with limited functionality, for example the popular orthophoto engines which do little more than generate orthophotos from the user's raw images and DTMs. Included here are five of the vendors mentioned above - Galileo SISCAM, ISM, KLT, Kork (now Vision) and Matra - but more recently the remote sensing software suppliers have ventured into this area, for example PCI have DTM and orthophoto modules, both for aerial photos and for SPOT imagery, forming part of its EASI/PACE package, and Earth Resource Mapping are extending the photogrammetric components in their ER Mapper suite. TNT-MIPS from MicroImages is another well known remote sensing and image processing package that offers orthophoto and DTM capabilities and will be extended to stereoscopic viewing.

Lohmann *et al.* (1990) and Dowman (1991b) attempted to grapple with this rich variety; the latter proposed a simple classification into four categories:

A performance and function of an analytical plotter with automatic feature extraction

B performance and function of an analytical plotter with image processing and computer assisted feature extraction

C systems designed for specific applications with high performance but limited functionality

D limited performance and functionality but low cost.

Today we still value such an approach, but perhaps a very practical taxonomy has merit too. Note that the above paragraphs represent a most rapid market survey of systems known to the authors. Doubtless some important systems have been omitted. We do not survey systems in academic and research institutions which are not widely offered on the open market and little attention is paid to systems aimed purely at close range photogrammetry. Five categories appear to emerge:

1. DPWs from major players offering the great majority of photogrammetric functions: Intergraph, Leica-Helava, Matra, Vision International, VirtuoZo, Zeiss
2. DPWs from smaller vendors offering less than complete functionality, but with great strengths in limited areas, such as feature extraction; often these workstations were designed primarily to emulate APs: DAT/EM, ISM, KLT
3. systems tuned to one function, which is offered at an economical price; these systems do not aspire to be fully functional DPWs: Vexcel Imaging (triangulation), Vexcel (close range), ISM (orthophoto), Vision International (orthophoto)
4. photogrammetric modules from the remote sensing vendors, usually offering orthophotos and perspective scenes and, less often, DTMs: PCI, ERDAS, Earth Resource Mapping, MicroImages
5. systems with limited functionality, yet still offering a wide selection from the DPW spectrum of operations, all at a low price (DVP, R-WEL, VTA).

### 1.4 The last four years

As part of the historical process outlined above, the vendors mounted an aggressive display at the ISPRS Congress in Washington, D.C., in 1992. The photogrammetric community awaited the rapid adoption of the new technology, yet the Congress was followed by a long period of slow sales. Perhaps this was a time of contemplation when users made up their minds whether to switch or to continue with AP technology (Petrie, 1992); perhaps it was a cyclical dip in the G7 economies. In due course there was a recovery and buyers became active again but, intriguingly, both analytical and digital systems were sold in greater numbers as a result. In the period 1994-96, Leica SD2000/3000, Zeiss P3/33 and Adam Promap APs sold in large numbers, enjoying a trend that if anything was slightly upwards, but simultaneously many users turned to digital and there were even a few who jumped directly from analogue to digital. One factor was the traditional suppliers' natural protectiveness towards their core technologies, resulting in aggressive selling and highly competitive pricing. Another was the dominance of Intergraph in the early 1990s and the wish of its competitors to close the gap. And a third was the realisation on the part of users that digital photogrammetry enabled them to offer a greater range of deliverables to their clients, who in turn were ready for products like DTMs and image maps and were often in the GIS business and happy to populate their raster layers.

## 2. HARDWARE

Section 2 describes the hardware components of a DPW, whereas discussion of the software is held over until section 3.

### 2.1 Principles and basic components

A DPW consists of a graphics workstation with enhanced image processing, memory and display capabilities including, in most but not all cases, a facility for stereoscopic viewing.

### 2.2 Host computers

A powerful processor (CPU) and a very large memory are required to handle the large volumes of image data. One can discern trends through the four years, for example in the computer platforms used and in the range of functionality in the software. Photogrammetrists have been complaining since the 1950s that the available computers are insufficiently powerful for their needs, but both workstation and PC platforms have developed to the extent that they are now adequate for most aspects of digital photogrammetry. Raw processing power, for example, allows DTMs of half a million points to be generated in under an hour, or orthophotos to be produced in a few seconds per megabyte. The most popular hosts are the Intergraph Clipper, Sun SPARCstation and Ultra, Silicon Graphics (SGI) Indy and Indigo$^2$ and top end PCs, usually Pentium-based. Many earlier machines, such as SPARCstation 2s and 10s and 80486 PCs remain in use. Typically 64 MB of RAM are recommended, though in some cases the methods used to handle the graphics for stereoscopic viewing make greater demands (see 2.3 below). The majority of these hosts operate under some brand of the Unix operating system, such as Intergraph's Clix, Sun's Solaris or SGI's IRIX. The PC solutions run mainly under Windows 3, but at least one vendor prefers DOS and some of these systems are at the time of writing being ported to Windows NT or 95.

**2.2.1 Accelerators.** In the past it was customary for DPWs to contain extensive custom built electronics. The DSCC mentioned above had very few off the shelf components and even its successor the DE/s (Digital Extraction Segment), of which DMA took delivery of several hundred from 1986 to 1993, relied on custom built disk arrays for data storage. There have been units which have used digital signal processing chips (DSPs) or array processors to cope with the computationally intensive processes required for image matching, but the latest workstations have enough power to handle these with off the shelf components.

Much more common, however, are graphics accelerators. A weak point in DPWs has always been the special hardware necessary for image panning and stereoscopic display.

Whereas expensive, custom built solutions had been very acceptable in the military systems of the 1980s, there has been a shift towards more modestly priced hardware and, indeed, the graphics engines offered by workstation manufacturers in their standard configurations have become sufficient. Such devices are required for stereoscopic viewing, unless split screen is used, because the graphics cards supplied as standard with most workstations either have too slow refresh rates (over 100 Hz is required) to display the left and right images alternately on the screen in fast enough succession to please the human eye, or because there is no convenient way of handling two images. Helava and Intergraph led the way with VITec-30 and VITec-50 processors and boards from companies like 3Dlabs, Peritek and Teksource have been used too. Note that while some of these processors have on board VRAM, others make use of imagery held in main system RAM. So in the case of the Creator 3D graphics of the Sun Ultra, for example, Leica-Helava recommend at least 128 MB RAM. These graphics sub-systems also help with image roaming, though skilful use of their firmware is required to achieve smooth motion at sufficient refresh rates. In many cases, image roam is still achieved only piecewise, i.e. within the imagery stored in the VRAM or the system RAM allocated to graphics. Smooth roaming over an entire stereo model with heavy graphics overlays of vector data or contours has barely been achieved with off the shelf hardware. Naturally, the fastest transfer of data is critical between VRAM, RAM and hard disk. It is interesting that Sun has moved off its long established SBus for the graphics of the higher end Ultra models and SGI's reputation for fast graphics has been founded to some extent in its excellent use of the PCI bus. While it is not unreasonable for users to demand the same smooth roaming all over the image that they have enjoyed for two decades with APs, it is worth noting that this is a real issue only with feature extraction - in most other digital photogrammetric operations it is of little significance. Many operators, too, having tried the DPW roaming and found it to be inferior to APs, change to fixed image moving cursor mode and become quite content.

Special hardware has also been used for compression. The JPEG board offered as an option by Intergraph, for example, has been very successful, though the latest workstations can perform software compression at more than one MB/sec and are fast enough for decompression on the fly during processing.

**2.2.2 Storage and archiving.** It has already been stated that the large data volumes make heavy demands on storage. The host computers are usually supplied with at least one internal hard disk of 1-2 GB and, usually, one or more external hard disks of 2-9 GB each. Thus many users take delivery of systems with 5-10 GB per workstation and in many cases expand on this soon after. In most cases the SCSI-2 standard is preferred but fast and wide SCSI-2, offering 20 MB/sec, i.e. twice as fast, is available as an option on most workstations and is standard on some models of the Sun Ultra. Power users sometimes opt for RAID technology, not so much to take advantage of its data security features but to obtain high speed and very large capacity with a single SCSI-2 device. RAIDs of 10-60 GB are quite common.

The data volumes preclude the use of floppy disks, even modern high capacity models, for other than control files, orientation results or vector data. QIC tapes, with capacities typically below one GB, are also rather unsuitable. Despite capacities currently of around 650 MB, CDs have become quite popular, especially as a means for users of DPWs to supply final deliverables to their customers. CD juke boxes ameliorate the problems, but 650 MB is sufficient to contain only one stereo pair of 12.5 μm images. Optical disks, which are currently increasing from 1.3 to 2.6 GB, have rather more potential than CDs, but appear to be handicapped by a multiplicity of standards and formats. Old fashioned reel to reel tape drives are becoming less common but still find use as input devices for remotely sensed data, of which they were the standard distribution medium for many years.

The industry seems to have settled for the moment on high capacity tape cartridge technology for off-line storage and archiving. The popular DAT and Exabyte equipment, for example, uses helical scan technology for writing and reading the data. Exabyte capacities are 7 -14 GB per tape depending on the effectiveness of in-built compression firmware. More recently, vendors such as Sun have announced even higher performance DLT (digital linear tape) units with 20 GB or more per tape. In most cases juke boxes are available, but it must not be forgotten that back up and restore are lengthy operations: at one MB/sec peak rate, for example, it may take several hours to read one tape.

### 2.3 Viewing systems

**2.3.1 Monoscopic or stereoscopic?** Photogrammetrists have been preoccupied with stereoscopic viewing for decades and this has been a big issue with DPWs too, but it is necessary to pause to review the situation and discern the directions for the near future. Many operations in digital photogrammetry are not stereoscopic at all and in this respect DPWs differ from APs: project management, image import, automated aspects of triangulation, DTM generation, orthophoto computation and mosaicking, perspective scenes and image map production are all entirely possible monoscopically. Only three operations are inherently stereoscopic: (i) measurement of ground control points, where a single monoscopic measurement followed by image matching for transfer to all the other images may be satisfactory for targetted points but is likely to be a source of error in all other cases; (ii) editing of automatically generated DTMs; and (iii) feature extraction. The last two of these, however, will become increasingly automated, as the discussions in sections 3.4 and 3.6 below conclude. Moreover, the trend towards head-up digitising on digital orthophotos seems to be a strong one. Thus stereoscopic viewing will be needed on a decreasing proportion of the DPWs at each site.

**2.3.2 Monitors.** Whether there is stereoscopic viewing or not, almost all DPWs have at least one monitor on which several windows appear, one or more of them containing imagery. In some cases this imagery may be 24 bit colour, which is best displayed in 24 bit colour. Thus a high quality monitor with high resolution is mandatory. The use of 640 x 480 VGA displays is a thing of the past! Probably 1280 x 1024 is the most popular resolution, but values around 800 x 600 are sometimes used with entry level systems and Intergraph showed the way with its "two megapixel" screen used from the early days of the ImageStation at the beginning of the decade. The systems which include a second monitor for the stereo display almost invariably offer a high quality 1280 x 1024 unit, but note that the number of "stereo pixels" generated by the graphics-subsystems is smaller than this. The Leica-Helava systems, for example, have offered a range from 640 x 480 on VITec-30 and 640 x 492 on SGI XL to 960 x 680 on Sun ZX and Creator 3D and probably 1024 x 768 on SGI High Impact.

The floating mark is created by using of a cluster of pixels to form a cross, circle or other preferred pattern. This moves, of course, in single pixel increments, which can be a little disturbing in that to an experienced AP operator movement may appear to be jerky or insufficiently precise, though for practical purposes it is quite adequate. Experiments by Mikhail (1992), Madani (1993) and Walker (1995) indicate, however, that with image resolutions of perhaps 20 µm or better DPWs lose little in measurement accuracy compared to analytical plotters. Two modes of movement are possible: fixed image moving cursor is much easier to implement than fixed cursor moving image owing to the hardware limitations noted above. Sub-pixel movement has been achieved by custom built hardware in military systems but has been little offered by commercial vendors. It is possible only by using zoomed images, though Zeiss has apparently used aliasing, i.e. small changes in the shape of the cursor, to achieve an optical effect similar to sub-pixel movement.

**2.3.3 Stereoscopic viewing.** A useful account of all the possibilities for stereoscopic viewing was given by Petrie (1983) 13 years ago! A strong argument can be made that the best way to achieve stereoscopic viewing is by displaying the left and right images on separate monitors. This was achieved in the expensive DSCC, for example, by means of optical trains, but it has not been popular in commercial systems partly because of cost and partly owing to technical difficulties. Nevertheless, Matra used an arrangement of two monitors at right angles, with horizontal and vertical polarisations sheets in front of them and a semi-reflector between them to give the required superimposition. The low cost DVP system from Leica has split screen stereo, i.e. the left and right images are displayed alongside one another and viewed through a simple stereoscope. This works well enough and is inexpensive, though the number of pixels in each window may be quite small, but the use of the same stereoscope has not proved popular with the Leica-Helava systems, which also have split screen stereo as a standard function on the console monitor. The split screen approach, of course, permits only one operator to view the stereoscopic image, whereas the methods described below enable several people to see the imagery in stereo at the same time.

The most popular solution for stereoscopic viewing has proved to be the display of left and right images, in quick succession (60 Hz per image, giving the 120 Hz figure noted above), on the same screen, which is viewed through a system developed for just this purpose. One or two systems, such as the R-WEL DMS and the early Terragon system, use an inexpensive anaglyph approach, by displaying the two images in red and green; as in its use in Multiplex and similar plotters, this approach is limited to black and white imagery. Two technologies are in more common use. The more popular, and less expensive, is CrystalEyes® from the StereoGraphics Corporation, where the screen is viewed through eyewear containing PZLT or LCD alternating shutters which are synchronised with the image display by direct wiring to the controller or by an infrared emitter usually mounted on top of the screen. The information to achieve this synchronisation is obtained via a port on the graphics sub-system located beside the connector for the RGB cable. Although the only requirement of the monitor is the high refresh rate, rather few monitors are available in sizes greater than 21 inches. In addition to Intergraph's excellent 27 inch units, there are only one or two monitors in each of the 29, 33 and 37 inch sizes.

The alternative to CrystalEyes® is polarised viewing, where a bezel containing an electronic prism is mounted on the front of the monitor and is synchronised using the same data from the graphics sub-system as was mentioned above; this polarises the left and right hand images in clockwise and counter-clockwise directions. The screen is viewed through polarised spectacles. The addition of the bezel makes the monitor rather expensive and the range of sizes available is small. The main manufacturer of these systems is NuVision, a spinoff company from Tektronix in Beaverton, Oregon. The 19 inch size has been the most popular, though a number of 17 inch Tektronix systems are in use and were offered by several vendors including Matra. The spectacles are lighter weight than for CrystalEyes®, do not need batteries and are much less expensive. NuVision systems seem to be preferred at present by vendors offering dual screen systems, whereas they are not used at all in single screen ones.

Stereoscopic DPWs may be further classified according to the number of monitors supplied. Some vendors offer single screen systems, which obviously cost less than dual screen, at the danger of having a rather cluttered screen. The CrystalEyes® system is preferred for these systems, because it works with virtually any fast refresh monitor and its basic cost is lower than NuVision. Other vendors prefer dual screen approaches, arguing that the second screen is used only for the stereoscopic image and so is less congested and so more relaxing for the user. Leica-Helava use the term “extraction monitor” for this “second head”. Though the vendors of two screen systems offer both viewing systems, there is a slight preference for NuVision, probably owing the lighter, less “scifi” appearance of the spectacles and the lower cost of replacement or furnishing multiple sets for “plotting by committee”. Also, it is common to suffer severe flickering when viewing the console monitor through CrystalEyes® eyewear, because it is out of synchronisation with the stereo monitor; thus the two screens should be set with a significant angular distance between them, so that the eyewear switches off when the operator turns his/her head sufficiently away from the emitter. There is no problem viewing the console monitor through the NuVision spectacles. The comparative quality of the stereoscopic image seen with the two systems seems to be a matter of taste, depending as much on the individual operator and ambient light conditions as on the viewing technology itself.

**2.3.4 Superimposition.** Since its first appearance early in the 1980s, superimposition of vector data over the stereoscopic image has been an important topic for APs and, to a much lesser extent, for analogue plotters. It has been acknowledged that the role of superimposition for quality control through on-line checks on both accuracy and completeness is a useful one and that it makes photogrammetry a much more productive tool for map revision, but it is an expensive option. On DPWs, however, it is possible to have colour, stereo superimposition as a standard feature. It is purely a matter of software to achieve this and many of the graphics boards include hardware or firmware to assist the process.

## 2.4 Control devices

There is a feeling in the industry that DPWs are computer based and movement in the imagery should be performed by means of computer devices, i.e. mouse and keyboard. This is not necessarily ideal for photogrammetrists, who are used to precise positioning and contouring using devices refined over decades for maximum accuracy and comfort, such as free moving hand controllers, hand wheels and foot disks. The use of foot switches for data collection is also common as an alternative to mouse buttons.

Not surprisingly, therefore, DPW vendors have been offering a multiplicity of devices to meet this requirement. Again, Intergraph have played a pioneering role by offering a variant of their distinctive hand controller seen first on the IMA AP. In digital photogrammetry, of course, the hand controller should incorporate buttons to perform a wider range of tasks than on APs, for example changing level in the image pyramid, varying brightness and contrast or switching between stereo models. The Intergraph device operates on a digitising tablet and Zeiss have similarly developed the P-mouse from the P-cursor developed for the P3 AP. DAT/EM, too, offer such a device. Matra brought the distinctive roller ball and thumbwheel controls of the Traster 77 to the T10 and Leica-Helava have simply utilised the hand controller from the SD2000/3000 line but more recently have switched to a newer device based on mouse technology, very similar to that offered for some time by Vision International. Helava have had access to studies on control devices carried out for military purposes and, although some of the military systems incorporate specially built force sticks, the standard offering by Leica-Helava is mouse for xy and a simple trackball for z! Most vendors offer hand wheels and foot disk as an option, though only ISM has displayed these devices frequently.

It would not be difficult to demonstrate that the overall working environment of DPWs has been the subject of less thought than in the case of APs, mainly because of longevity and because the latter are heavier and have a rather inflexible relationship between the operator and the oculars. But many vendors do offer adjustable computer tables, usually with either a raised area or moving platform(s) to accommodate the big monitor(s) in the position(s) preferred by the operator. Many of these tables can be moved vertically by means of mechanisms on the legs and further degrees of freedom are incorporated in the chairs.

### 2.5 Networking aspects

The large data volumes mean that data transfer is just as critical an issue as data storage. On the scanners, for example, it is usually faster to scan to local disk than to a disk on the destination DPW. Similarly, DPWs can use file servers as big data repositories, but local disk access is faster. Technology exists for RAIDs to be shared by more than one host computer.

In most cases so far, conventional Thin-Wire or 10-BaseT Ethernet has been used for digital photogrammetric applications, though the transfer of big digital images delays most other network traffic. 100-BaseT is available as an option on most systems and as standard on one or two. A few users opt for FDDI networking but as yet rather few digital photogrammetrists have explored ATM.

Since many DPW purchasers have existing company networks connecting their analogue plotters, APs, printers, plotters, etc. and since high speed network links are expensive, there has been a slight trend towards mixed networks, where 10-BaseT and 100-BaseT links can be mixed through switching hubs. Often it is necessary to accommodate more than one protocol, for example a group of Unix DPWs communicating with TCP/IP may also have to use DECnet protocols to be understood by an existing in-house network.

Printers and plotters are typically connected by parallel or serial line to one workstation and accessed by the others through the network. In one or two cases, such as the FIRE 2240, the device is SCSI-2. The laser raster plotters often have their own host computer containing the RIP, so this also is on the network. Naturally it is sensible to select a DPW without expensive stereoscopic viewing if one station is apt to be heavily committed to printing or plotting.

### 2.6 Output devices.

Vector plotters are not unsuitable for DPWs: they are perfectly good for displaying the vector data which is all that a number of users extract on DPWs. Similarly, raster devices are suitable for outputting vector data from either APs or DPWs, but are essential for image products. These devices range from inexpensive inkjet plotters from companies like Hewlett-Packard or ENCAD, which have become enormously popular for outputting short runs of image maps on paper or, less often, on film and are even used for proofing. More expensive and also higher resolution are thermal transfer and dye sublimation devices like the Tektronix Phaser III and Kodak XL7600, though these are typically limited to A4 or A3 format. Colour laser printers and plotters are emerging now from companies such as Hewlett-Packard and Xerox.

Superb performance is available from three different types of plotter at the high end of the price range. IRIS's variable inkjet technology produces superb plots on paper or film and is often used as a proofer in top end systems. For the production of masters to be used as the basis of published maps there are film recorders, which are devices producing continuous tone of limited format, such as the FIRE 2240 from Cymbolic Sciences International, from which final documents are made by means of enlargement and half-toning in a conventional cartographic process. Alternatively, large format laser raster plotters are highly sophisticated systems in which the raster image is numerically convolved with the equivalent of a dot screen by a custom built hardware and software raster image processor (RIP) and the result streamed out to the laser plotting head. These plotters are produced by specialist companies in the print industry such as Barco Graphics, Dainippon Screen, Linotype-Hell and Lüscher. Like the film recorders, these devices are expensive, leading to increasing use of bureaux rather than in-house services for fine outputs.

## 3. SOFTWARE

This section commences with an overview of the operation of a DPW, which enables a proper understanding of the basic software. It continues with a discussion of each of the main photogrammetric application areas.

On the software side, a schematised workflow is used as a yardstick to assess to what extent the different vendors offer the complete range of digital photogrammetric operations. It is found that almost all DPWs are capable of emulating analytical plotters and of generating orthophotos, but fewer include functions like automated generation of digital terrain models (DTMs), mosaicking and perspective scenes. Map finishing and sophisticated project management are even less common.

Few vendors have written all their software themselves and imported components tend to recur, just as car manufacturers use one another's engines to obviate development costs. Two vendors have purchased small software houses specialising in packages for map compilation, to enlarge their capabilities in-house. The capture of data directly into the popular MicroStation CAD package is offered by most vendors.

### 3.1 Overview

The fundamental operation of a DPW is rather similar to an AP. The projective geometry and mathematical models in a DPW are very similar to those of the AP with object coordinates primary, a concept explained by Petrie (1990). The inputs, in other words, from the operator via the control devices, are construed as XYZ motions in object space and are transformed into changes in the positions of the cursors on the individual images. This transformation is performed with the collinearity equations or, in the cases of certain types of imagery, some other suitable ground to image transformation. Note that in the DPW there may well be more than two images, for example four can be displayed in two screen systems or others may not be displayed at all until called up. Thus the real-time operations of DPWs and APs are fundamentally the same, though the former always include image processing software too, for example contrast enhancement and filters. Both DPWs and APs, of course, can vary brightness, the latter by illumination control.

The sections below examine some aspects of DPW software according to the different applications. It is seen that the main photogrammetric functions - triangulation, DTMs, orthophotos and feature extraction - are offered only in the packages from the traditional photogrammetric suppliers, whereas only a subset of these functions is available from many others such as the remote sensing vendors.

### 3.2 Imagery and mathematical models

All DPWs considered for this paper handle aerial photography. Many of them also include facilities to treat some satellite data, usually stereo-SPOT imagery. At the other end of the equation, there is considerable variety in the ability of the different DPWs to handle coordinate systems and map projections. The most flexible include a range of coordinate systems, datums, ellipsoids and projections, plus the possibility for the user to program others, whereas more limited DPWs have a very small range indeed.

### 3.3 Orientation and triangulation

Naturally, every DPW must include some facilities for orientation. Interior orientation is mandatory and even the simplest orthophoto engine, for example, must include a space resection. Some systems have impressive automated functions, the interior and relative orientation in the Zeiss PHODIS being perhaps the best known. Owing to their rather different history, DPWs often have orientation philosophies based on bundle adjustment without the traditional sequential relative and absolute orientation, though in the Leica-Helava DPWs, a button has been added so that the classical approach may be chosen as an option. In many cases, even if complete automation of the orientation is not there, image matching may be selected to refine the position of a point which has been manually selected or measured in one of the images.

The strengths of a DPW are very apparent in the process of triangulation. Though most vendors have adopted a data capture approach rather similar to that found in many analytical plotters, i.e. working along a strip at a time, with model formation, point transfer, measurement and blunder checks. The same process on a DPW, however, benefits from being able to display more than two images at once, to switch rapidly between them and to recall earlier images for remeasurement without pain. The user interface in the Intergraph ImageStation, for example, has proved very effective (Kölbl, 1996).

Highly automated triangulation is a more recent development which marks out digital photogrammetry as a step forward. In principle, the overall configuration of the block may be derived from GPS data for the exposure stations or from manual inputs of forward and side overlaps and the offsets between exposure stations in the individual strips. If each ground control point is identified and measured manually in at least one image, then the remainder of the work can be done automatically, i.e. control points can be transferred, and pass and tie points selected, measured and transferred. The automated process can include error detection, for example by model and strip formation, followed by rigorous bundle adjustment with data snooping to provide a second level of blunder detection. Several groups have been working intensively on this, for example Helava, Zeiss, Inpho and Ohio State University. A summary is given by Fritsch (1996).

Broadly speaking, the groups divide into two schools of thought. The Helava approach is to define a pattern for tie points, thereby fixing the image positions in the first image in which they appear, and then search for the positions in the other images and measure them by image matching. Failures, often caused because the forward and sidelaps are incorrectly defined, are measured manually. The other approaches use interest operators to find points, which are therefore not limited in number and may be very dense indeed. Probably the former approach is more operational at present, the Helava Automated Triangulation System having been installed by Leica-Helava on many sites (Miller and Walker, 1996). Interestingly, at least one user of the Leica-Helava system has experimented with very large numbers of tie points, making no attempt manually to measure bad points, i.e. simply omitting failed points from subsequent stages of the computation. However unsatisfactory this sounds, it appears to work!

### 3.4 DTMs

The generation of DTMs by image matching has been a *raison d'être* of digital photogrammetry. This is not the place to attempt to encapsulate the efforts of a generation of researchers. It is enough to say that the method is now highly sophisticated and rather successful, though results are still unpredicatable in featureless image areas or at discontinuities such as buildings or trees in large scale photography. Modern host computers are so powerful that automatic generation of over 500,000 points per hour is possible, but powerful interactive editing tools are the key to satisfactory final results. The two best known techniques are the area based matching of Leica-Helava, based on Hierarchical Relaxation Correlation (Helava, 1988; Miller and Devenecia, 1992), and the interest operator approach of MATCH-T, the Inpho product subsequently adopted by Zeiss, Intergraph and DAT/EM (Krzystek, 1991). Matra and ERDAS/Vision International utilise proprietary techniques and some vendors, such as ISM and KLT, do not offer products in this area.

Interestingly, the stress on automatically generated DTMs means that many DPWs are not equipped with the sort of manual DTM capture functions which are a mainstay of APs. Without these functions, editing of erroneous elevation data is a most difficult operation. The subsequent stage of the process is important too, i.e. the use of DTMs for contouring, generation of triangulated irregular networks (TINs), computation of profiles and cross-sections, etc. Leica-Helava, for example, offer KLT's excellent TIN module, whereas for customers using MicroStation they have opted for the TerraModeler TIN package from the Finnish company Terrasolid Oy.

### 3.5 Orthophotos, mosaics and image maps

Like DTMs, orthophotos are one of the driving forces in the adoption of digital photogrammetry. Every vendor offers this facility. There are differences in sophistication, for example some approaches are completely rigorous in their pixel by pixel computation, others utilise some kind of anchor point method to save processing time; resampling algorithms vary too, but simpler methods like nearest neighbour, bilinear or bicubic resampling suit most requirements. Typically, orthophotos can be generated in a few seconds per MB. One or two vendors have added "true orthophotos", in which the effects of building lean are rigorously removed provided that the building tops are measured and the bottoms lie on the DTM. DPWs can easily generate stereomates, but this seems less important today than it was in the 1960s. Indeed, there seems to be a gathering force towards simple head-up digitising from digital orthophotos as an alternative to conventional stereoscopic methods of feature extraction: the digital monoplotter of the 1970s and 1980s is undergoing a revival, though the orthophoto, with or without DTM, appears to have replaced the raw image and DTM of former times.

While many users attempt the acquisition of pinpoint photography in order to make orthophotos from single aerial exposures and thus avoid mosaicking - a reasonable task now that in-flight GPS is with us, most systems have mosaicking. While some systems join orthophotos together with radiometric and geometric feathering, others treat a mosaic as nothing more than a single orthophoto produced from a collection of input images, a quite logical approach. In both cases, however, user definition of seamlines may be necessary to avoid the unpleasant effects of seamlines going through buildings.

The addition of marginalia and graphics overlays to the mosaic to form an image map is provided in many DPW and remote sensing packages. Some are quite sophisticated, but others are quite simple, to the extent that a market niche has been identified for map finishing software: for example, the Canadian company 2+1, a partner company of PCI, has moved smartly to fill this gap with its ACE product. Often the software accompanying high end plotters provides this functionality also, for example Mercator from Barco.

### 3.6 Feature extraction and GIS

In practice the last four years have witnessed considerable activity to make available on DPWs the same software packages for feature collection that have served their users well on analogue and analytical workstations. This has included, of course, DPW vendors porting their own software to the new workstations. The process was facilitated by two purchases of software houses: Vision International bought KORK and Zeiss brought DDI, the producer of CADMAP. Thus Leica-Helava, for example, offer ATLAS, CADMAP, DAT/EM and PRO600, Zeiss offer PHOCUS and CADMAP, Vision offer KORK and DAT/EM, etc. Led by Intergraph, almost all vendors offer on-line data collection into Bentley Systems MicroStation.

Arguably, the software for feature collection is not as refined as on the earlier generation of workstations. The software choice outlined in the previous paragraph is not as wide as before. The implementations have not had as many labour years devoted to them. This situation, of course, is improving as we write.

There has been a trend, which DPWs have experienced in common with the previous generation of workstations, towards the generation of digital data rather than the production of aesthetically sophisticated maps. Thus many of the most popular data collection packages are interfaces to CAD packages, especially MicroStation, which is the on-line software offered by most of the vendors. GIS packages are less common and probably GeoCity, PHOCUS and System 9 are the only ones seen on-line on DPWs.

But perhaps the greatest disappointment in digital photogrammetry is that as yet few DPWs offer any significant automation in feature extraction, notwithstanding the fact that this area has been one of the most intense research areas for decades. True, a valuable result of this work is knowledge based extraction of attribute information from imagery, for example many workers have successful identified most or all buildings in their sample imagery. But the rationale behind this work has not been measurement and, arguably, more useful to the practising photogrammetrist are tools which can rapidly and accurately measure features identified by the human operator as requiring to be mapped.

Many vendors are working on this problem. The DPWs sold by Leica are benefitting from much work being done by Helava and its parent company, GDE Systems, some of it originating in US military projects. While attribute extraction has received much attention, work has also been done on edge extraction, classifiers, Z finding, snakes, region growers, squaring, splining, thinning, blunder detection and other methods. The result is that the product sold in the commercial market-place now includes tools for building measurement, feature delineation and area measurement. The first works from fast, approximate measurement of building corners by the operator, finds the edges of the roof, computes the corners and squares the building. Tests have confirmed beyond reasonable doubt that the use of this tool allows two to four times as many buildings to be extracted as completely manual measurement, with a significant reduction in fatigue. The second tool permits the operator to position the floating mark at a few points near a linear feature such as a road edge; the edge is then determined accurately along its length. The third tool requires the operator to place a seed in the area to be measured, for example a lake, and two seeds outside; it then finds the area and delineates it. In all cases the philosophy is "refinement", i.e. improvement by image processing of information input by the operator. Productivity is further enhanced by setting defaults, i.e. for each feature code pre-allocating the most appropriate measurement tool. The next stage will be to develop edit tools to overcome the most common errors in the automated processes. Vendors have a wealth of research work available for productisation.

### 3.7 Perspective scenes and simulation

The generation of perspective scenes or "birds eye views" either singly or in animated sequences as "walk throughs" or "fly throughs" has created considerable interest. Most vendors have this function and it has proved especially popular with the remote sensing software houses, for example ER Mapper and the PCI FLY product, provided that DTMs are available. Earth Resource Mapping and VirtuoZo have exploited the hardware strength and geometric engine of the SGI Indigo$^2$ workstations to enable the operator to change the viewpoint in real time. The GDE Systems RapidScene product achieves the same through the use of powerful add-ons by Evans and Sutherland to a high end SPARCstation. In many cases the final products can be monoscopic or stereoscopic, though most vendors do not yet have automated flight path creation to enable the stereoscopic pairs of views to be created automatically. While the applications of perspective scenes are legion in the remote sensing area, where the draping of the imagery on the DTM offers a most informative tool for interpretative purposes, thus far it has been used rather less in what may be considered to be its main non-military home - planning. One counterexample is given by Simmons (1996), where it has been used in a planning enquiry associated with the UK rail link from London to the Channel Tunnel.

## 4. CONCLUSIONS

### 4.1 How well have we done?

Any assessment of the success of DPWs must focus on the issue of automation, which follows logically from the use of digital images and thus must ultimately distinguish DPWs from earlier generations of photogrammetric instrumentation. The extent to which automation has pervaded DPWs is disappointing. "Easy" automation such as the generation of orthophotos, of course, is omnipresent. Many DPWs have some level of automation in their orientation, but relatively few offer highly automated triangulation. DTMs have been a research challenge for decades and not all vendors have developed in-house solutions. Mosaicking, too, has proved intractable in some respects, but the most remarkable aspect is tools for automated feature extraction - the huge lag between achievements in research laboratories and what vendors judge to be robust enough for the market-place.

**4.1.1 Digital versus analytical.** Many discussions, as we have hinted above, tend to focus on the rather inappropriate debate of the virtues of digital against analytical. Nevertheless, many of the factors they adduce are well worth noting. The strengths of digital, for example, include the following:

- more functions and more products
- no repetition of interior or exterior orientation
- models ready to use immediately on completion of triangulation
- no calibration or wear and tear, i.e. all the expensive, high precision, mechanical components of the AP are eliminated in the DPW, as are the measuring components such as encoders; also, in most cases there are no optical components of the type found in APs
- development benefits from advances in computer technology
- easy hardware maintenance using computer manufacturers' service networks
- colour, stereo superimposition without additional cost
- scope for extensive automation in interior orientation, triangulation, DTMs, orthophotos, mosaics and feature extraction
- end to end workflow, giving greater simplicity.

The demerits include:

- additional cost of scanner; still significant if one scanner feeds several DPWs or if a bureau service is used
- poorer image quality than that traditionally provided by film imagery and optical trains
- less smooth image roaming than APs, despite expensive graphics sub-systems
- ergonomics less well thought out
- narrower range of proprietary and third party packages for feature extraction and GIS
- very large data volumes
- greater computer literacy required on the part of the operator
- more complex software, less easy to use, than APs
- lack of software for project management (APs do not have this either, but the need is less pressing)
- lack of standards, especially for image formats and quality control.

Dowman (1996) and Nwosu (1996) retain some doubts on the efficacy of DPWs *vis a vis* APs and the debate goes on. Two of their arguments are centred on the high cost of photogrammetric scanners and the lack of automation for feature extraction. The cost issue is complex, however, because DPWs ought to be compared with APs with colour, stereoscopic superimposition and the cost of the scanner should be distributed if it serves several DPWs or if a bureau service is used.

**4.1.2 Trends in the market-place.** Bearing the above in mind, let us consider briefly what has actually happened. After the 1992 Congress there was a hiatus, as we commented earlier. Perhaps the aggressive, pioneering stance of vendors at the 1992 Congress in Washington, D.C., caused prospective customers to delay and contemplate deeply on their choice of technology. The first result was a lull in all sales during this pause for thought. The second was that many then elected to be conservative and choose analytical plotters, sales of which have remained buoyant to his day! Since about 1994, however, numerous agencies have taken the plunge into digital photogrammetry. It must not be our role to compare the different vendors, but it would hardy be biased to state that in the workstation world Intergraph, Leica-Helava and Vision/ERDAS have led the way, alongside ISM on the PC. The overall scene is heterogeneous, with adoption not only geographically disparate but also spread through various market segments. Big internationally aided projects have been one source of early adopters, but numerous national and provincial mapping organisations have been quite adventurous. The private sector has adopted the new technology with enthusiasm too and a spate of advertisements and published papers indicates how many firms of all shapes and sizes plan to earn significant slices of their livings from digital orthophoto work, both as final image map products and for populating raster layers of their clients' GIS systems.

It is risky to introduce commercial, business issues into a scientific paper, but these have been important in the last four years of DPWs. Marketing clout, for example, may have been just as important as technical expertise in the success of some products. Worldwide presence, heavy advertising, participation in trade shows, high profiles in conferences, introductory offers, installation of evaluation systems at nominal cost, resources to participate in complex procurement exercises, etc., have been real influences on development. Vendors have a built in advantage on sites where their own equipment is already installed, benefitting those with a history of analogue or analytical workstations, analytical upgrades, software for map compilation, etc.

**4.1.3 Users.** The behaviour of the users is another source of insight into the evolution of DPWs. The majority of adopters, of course, have mixed systems consisting of analogue, analytical and digital workstations. A few organisations have jumped directly from analogue to digital, by-passing APs altogether.

Most users still scan film aerial photography in photogrammetric scanners. The majority possess an in-house scanner, sometimes from the same vendor as their DPWs, yet many use one of the increasing number of scanning bureaux companies which have sprung up, especially in North America, often by expanding existing business in photo processing. These firms often scan round the clock, gaining extensive experience and felicity with the scanner hardware and software, to offer a satisfactory, cost effective service. Most users produce DTMs, orthophotos, mosaics and image maps, often employing desk top publishing software like PhotoShop for map finishing. A lesser number use DPWs heavily for feature extraction. While all users have done some triangulation on DPWs for years, the appearance of the automated triangulation packages noted in section 3.3 above has spurred interest in exploiting automation for quite large blocks, despite the huge storage demands and the fairly daunting early versions of the software. The concept of not having to insert or set up models again after triangulation, regardless of how often or on which DPW they are required, is understood and perhaps taken for granted already, yet it represents highly worthwhile savings over APs. The export of orientation parameters to APs and even analogue instruments is embryonic, but necessary. Few users produce perspective scenes or carry out commercial close range photogrammetry on DPWs. Today's DPW solutions for the commercial market-place are suitable, often with little customising, for many military needs. Indeed, military and academic users are the main purchasers of vendors' modules for processing satellite imagery and the availability of software modules with mathematical models for several of the classified military satellites remains an important advantage of digital over analytical photogrammetry.

Users' concerns include fitting DPWs into their existing systems, so their demands are numerous: particular coordinate systems and map projections; incorporation of GPS data acquired during flight; continuing use of existing block adjustment package; formats for image, DTM and vector data; exchange of orientation data with analogue and analytical workstations; ergonomic environment in terms of stereoscopic viewing, xyz control devices, etc; same software for map compilation as on existing analogue and analytical workstations; and highly functional, heterogeneous computer networking of DPWs with one another, with scanners and with existing workstations.

The preponderance of digital orthophotos has been followed after some delay by the development of standards. ASPRS have a committee working on this area (Nale, 1995) and, *inter alia*, national mapping organisations like Geomatics Canada (Armenakis, Regan and Dow, 1995) and Ordnance Survey of Ireland are taking the issue very seriously indeed. Yet it is true to say that in 1996 standards for orthophotos are less widespread and less sophisticated than those for line maps. This is important, because so popular has digital orthophotography become that many mapping companies promote image maps as their premier service and the focus of attention has progressed from feasibility to production problems, for example Manzer (1995).

A debate of today concerns monoplotting. Digital photogrammetry opens up the chance of routinely performing head-up digitising on orthophotos. Indeed if one assumes that a DTM must have been available to make the orthophoto, then it follows that classical monoplotting with a raw image and a DTM is also possible and presumably more accurate since no resampling has taken place. A monoplotter can be created from little more than a CAD package such as MicroStation if it has the facility to handle an image layer, i.e. a rigorous photogrammetric package is not essential if an orthophoto is used. But it remains moot whether this approach, based on orthophotos which in turn are generated using DTMs of finite accuracy, and without stereoscopic viewing to enhance accuracy or interpretation, is good enough.

The above paragraphs are enough to hint at the amazing diversity of purchasers of DPWs, their existing methods and their applications. The result has been a series of enormous challenges for the vendors. The DPWs have had to be dovetailed into existing computer networks, data flows and data formats. The energetic competition between vendors has ensured their willingness to meet stringent customer requirements in terms of networking, customising, workflow design, provision of consultancy, etc. This has resulted in poor vendors and some highly sophisticated users. Nevertheless, many of these "top end" users have worked enthusiastically with the vendors to reach their goals in high tech partnerships. Competition has inevitably led to very fast development indeed: all vendors maintain high standards, so the need to honour commitments made during the winning of business has caused crisis development to take precedence over well thought out development plans, coupled with a rather high dependence on beta sites. On the other hand, this charged environment has undoubtedly accelerated the progress of the DPWs. One simple example illustrates the trend: it is now unexceptional for a customer to place an order for DPW software, with a stipulation that it must run on some computer model on which the software has not even been tried at the time of order!

Innovation diffusion is, therefore, in full swing. Aggressive sales and marketing by the main vendors, coupled with conservatism amongst some users, especially those with heavy workloads in feature extraction, have ensured buoyant sales of APs in the period 1994-96, but it is clear that the peak has been passed and the decline has begun. The last page is about to be turned of the AP story, a glorious chapter in the annals of photogrammetric instrumentation, and by 1998 it is likely that almost every sale of a new system will contain a DPW. Leberl's (1991) argument that the change from APs to DPWs would be faster than that from analogue plotters to APs is likely to prove accurate.

**4.1.4 Evolutionary or revolutionary?** It is trendy these days to rave about paradigm shifts. Does the general adoption of DPWs mean that we have enjoyed such an event in photogrammetry? In a cogent, mature look into the future almost two decades ago, Ackermann (1977) contrasted consolidation and incremental development with major leaps forward occasioned by the advent of computers and electronics in our instrumentation. In a later overview (*idem*, 1992), the same message was repeated, from rather later in the course of events. At the same time, Leberl (1991, 1992a) was evangelistic. More recently still, Ackermann is convinced: "The major technical breakthrough ... is the step towards digital photogrammetry... the development which now has started is so fantastic and has unlimited potential that I am not at all worried about future development... The result will supercede [*sic*] anything which we could ever have dreamt of, simply because of the power of digital technology" (Anon, 1995, pp. 41 and 45).

Ackermann (1977) and Leberl (1991) also contrasted revolutionary with evolutionary development. Such assessments are not particular to photogrammetry but are scattered through the advances of many sciences and humanities. Leberl argued that the change from analogue to analytical photogrammetry had been evolutionary and would prove to have been slower than that from analytical to digital, which was revolutionary despite the fact that much automation was not yet operational. More recently, however, others have taken up the cudgels in this debate. Wong (Anon, 1996) set out typically forthright views, saying that we were indeed undergoing a revolution, that one of the stumblingblocks was not technical but was the lack of full understanding of the processes and their true costs, and, indeed, "virtual machines" were here since technology would enable software to convert any PC into a DPW, opening access to all. This idea has some common roots, perhaps, with Leberl's phrase "democratization of photogrammetry" and one wonders, too, whether the client-server world or the Internet will encourage in the future the availability of bits of digital photogrammetric software to be grabbed and used when they are needed. It is churlish to dampen such excitement, yet the truth today may be that in terms of triangulation, DTMs, orthophotos, mosaics and perspective scenes, digital photogrammetry is revolutionary; with respect to the all important task of feature extraction, however, it will be but evolutionary until usable automation is included in most systems. Wong's phrase "continued evolution in automation" (*ibid.*, p. 54) juggled the words again, but is very pertinent; Dowman (1996) noted, too, that automation is partly successful and is spreading inexorably.

### 4.2 Future directions

It is absolutely certain that the DPW will supersede the analytical plotter very soon, though the potential of the latter for cost effective map compilation will ensure a continuing trade in used equipment. We see fluent, optimised flowlines emerging to give photogrammetry massive increases in productivity. Project management software, grown from intelligent photogrammetric applications of software tools designed for manufacturing industry, combined with sophisticated image databases and universal use of the Internet, will control and monitor the flow of processing, which commences with digital cameras and roll film scanners. GPS triangulation, DTM generation, mosaicking and feature extraction will be the mainstays, all benefitting from successful automation. Advances in map finishing will be welcome too. Windows NT solutions will appear. DPW software will become sufficiently refined and robust to equal that of analytical plotters in maturity and productivity. Remote sensing, GIS and photogrammetry may well converge, with all functionalities combined in every workstation. There will be greater use of client server approaches. A moving matrix of research organisations, vendors and their people will jostle to offer these exciting solutions. Continuing cut throat competition between vendors will keep prices and margins at their lowest ever, which may inhibit product development or even cause the demise of some weaker runners, though there will be no shortage of enthusiasts keen to join the race. All these directions are logical continuations of trends begun during the period 1992-96, when competition and technology interacted to offer users DPWs with attractive variety, capability, power, maturity and economy. When our successors make their report in the 2000 Congress, it will be a success story centred on reductions in the cost of mapping.

## REFERENCES

Ackermann, F., 1977. Some thoughts on the future of photogrammetry. The Photogrammetric Record, Vol. 9, No. 50, pp. 147-155.

Ackermann, F., 1992. Strukturwandel in der Photogrammetrie. Zeitschrift für Photogrammetrie und Fernerkundung, No. 1992/1, pp. 2-5.

Anon, 1995. GIM interviews Professor Fritz Ackermann, retired professor, Stuttgart University. Geomatics Info Magazine, Vol. 9, No. 10, pp. 40-45.

Anon, 1996. Facing the 'soft' future: GIM interviews Mr Patrick Wong, President of ISM. Geomatics Info Magazine, Vol. 10, No. 1, pp. 53-57.

Armenakis, C., Dow, A. and Regan, A.-M., 1995. Applications of digital photogrammetry at the Canada Centre for Mapping. Seventh International Conference on Geomatics, Ottawa, Canada, 12-15 June, 9 pp.

Armenakis, C., Regan, A.-M. and Dow, A., 1995. Softcopy photogrammetric applications for national topographic mapping. Geomatica, Vol. 49, No. 4, pp. 433-443.

Baltsavias, E.P., Li, H., Stefanidis, A. and Sinning, M., 1996. Automatic DSMs by digital photogrammetry. Surveying World, Vol. 4, No. 2, pp. 18-21.

Case, J.B., 1982. The digital stereo comparator/compiler (DSCC). In: International Archives of Photogrammetry and Remote Sensing, Vol. 29, Part 2, pp. 23-29.

Cogan, L., Gugan, D., Hunter, D., Lutz, S. and Peny, C., 1988. Kern DSP1 - Digital Stereo Photogrammetric System. In: International Archives of Photogrammetry and Remote Sensing, Kyoto, Japan, Vol. 27, Part B2, pp. 71-83.

Corbley, K.P., 1995. Iowa mapping firm meets growing custoemr needs with softcopy photogrammetry. Earth Observation Magazine, Vol. 4, No. 2, pp. 48-51.

Dörstel, C., 1995. PHODIS innovations. In: Fritsch, D. and Hobbie, D. (eds.), Photogrammetric Week '95, Wichmann, Karlsruhe, pp. 5-10.

Dowman, I.J., 1991a. Digital photogrammetric systems in North America. The Photogrammetric Record, Vol. 13, No. 78, pp. 931-934.

Dowman, I.J., 1991b. Design of digital photogrammetric workstations. In: In: Ebner, H., Fritsch, D. and Heipke, C. (eds.), Digital Photogrammetric Systems, Wichmann, Karlsruhe, pp. 28-38.

Dowman, I.J., 1996. Digital photogrammetry - time for decision. Surveying World, Vol. 4, No. 2, p. 5.

Dowman, I.J., Ebner, H. and Heipke, C., 1992. Overview of European developments in digital photogrammetric workstations. Photogrammetric Engineering & Remote Sensing, Vol . 58, No. 1, pp. 51-56.

Foley, B.L., 1993. Past, present and pricing of orthophotos. In: Clark, B.P., Douglas, A., Foley, B.L., Huberty, B. and Whitmill, L.D. (eds.), State-of-the-art mapping, Proceedings SPIE, volume 1943, Bellingham, Washington, pp. 242-245.

Fritsch, D., 1995. Introduction into digital aerotriangulation. In: Fritsch, D. and Hobbie, D. (eds.), Photogrammetric Week '95, Wichmann, Karlsruhe, pp. 165-171.

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, pp. 479-488.

Heipke, C., 1995a. State-of-the-art of digital photogrammetric workstations for topographic applications. Photogrammetric Engineering & Remote Sensing, Vol . 61, No. 1, pp. 49-56.

Heipke, C., 1995b. Digitale photogrammetrische Arbeitstationen. Deutsche Geodätische Kommission bei der Bayerischen Akademie der Wissenschaften, Dissertationen, Series C, No. 450, 111 pp.

Helava, U.V., 1988. Object space least squares correlation. International Archives of Photogrammetry and Remote Sensing, Kyoto, Japan, Vol. 27, Part B2, pp. 297-302.

Helava, U.V., 1991. State of the art in digital photogrammetric workstations. Photogrammetric Journal of Finland, Vol. 12, No. 2, pp. 65-76.

Johansson, M., Miller, S.B. and Walker, A.S., 1995. Digital orthophotography at the National Land Survey of Sweden. In: GIS/LIS '95 Annual Conference and Exhibition, Proceedings, Nashville, Tennessee, Vol. 1, pp. 522-529.

Kaiser, R., 1991. ImageStation: Intergraph's digital photogrammetric workstation. In: Ebner, H., Fritsch, D. and Heipke, C. (eds.), Digital Photogrammetric Systems, Wichmann, Karlsruhe, pp. 188-197.

Kirwan, R.A., 1995. Resurveying Ireland - experiences with digital photogrammetry. Geomatics Info Magazine, Vol. 9, No. 10, pp. 30-31.

Kölbl, O., 1996. Various triangulation packages OEEPE Workshop on the Application of Digital Photogrammetric Workstations, Lausanne, Switzerland, 4-6 March.

Krzystek, P., 1991. Fully automatic measurement of digital elevation models with MATCH-T. In: Ebner, H., Fritsch, D. and Heipke, C. (eds.), Digital Photogrammetric Systems, Wichmann, Karlsruhe, pp. 203-214.

Leberl, F.W., 1991. The promise of softcopy photgrammetry. In: Ebner, H., Fritsch, D. and Heipke, C. (eds.), Digital Photogrammetric Systems, Wichmann, Karlsruhe, pp. 3-14.

Leberl, F.W., 1992a. Towards a new photogrammetry. Zeitschrift für Photogrammetrie und Fernerkundung, No. 1992/1, pp. 9-12

Leberl, F.W., 1992b. Design alternatives for digital photogrammetric systems. International Archives of Photogrammetry and Remote Sensing, 29, No. B2, pp. 384-389.

Leberl, F.W., 1994. Practical issues in softcopy photogrammetric systems. In: Proceedings, Mapping and Remote Sensing Tools for the 21st Century, August 26-29, 1994, Washington, D.C., pp. 223-230.

Manzer, G., 1995. Practical considerations for avoiding problems in the production of digital orthophotos. Geomatica, Vol. 49, No. 4, pp. 455-462.

Madani, 1993. How a digital photogrammetric workstation is compared to an analytical plotter. In: Clark, B.P., Douglas, A., Foley, B.L., Huberty, B. and Whitmill, L.D. (eds.), State-of-the-art mapping, Proceedings SPIE, volume 1943, Bellingham, Washington, pp. 266-276.

Mikhail, E.M., 1992. Quality of photogrammetric products from digitized frame photography. International Archives of Photogrammetry and Remote Sensing, Vol. 29, No. B2 pp. 390-396.

Miller, S.B. and De Venecia, K., 1992. Automatic elevation extraction and the digital photogrammetric workstation. In: ASPRS Technical Papers, 1992 ASPRS-ACSM Annual Convention, Albuquerque, New Mexico, Vol. 1, pp. 572-580.

Miller, S.B., Helava, U.V. and Devenecia, K., 1992. Softcopy photogrammetric workstations. Photogrammetric Engineering & Remote Sensing, Vol. 58, No. 1, pp. 77-84.

Miller, S.B., Thiede, J.E. and Walker, A.S., 1992. A line of high performance digital photogrammetric workstations - the synergy of General Dynamics, Helava Associates and Leica. In: International Archives of Photogrammetry and Remote Sensing, Kyoto, Japan, Vol. 29, Part B2, pp. 87-94.

Miller, S.B. and Walker, A.S., 1993. Further developments of Leica Digital Photogrammetric Systems by Helava. In: 1993 ACSM/ASPRS Annual Convention & Exposition, Technical Papers, New Orleans, Louisiana, Vol. 3, pp. 256-263.

Miller, S.B. and Walker, A.S., 1995. Die Entwicklung der digitalen photogrammetrischen Systeme von Leica und Helava. Zeitschrift für Photogrammetrie und Fernerkundung, No. 1/95, pp. 4-16.

Miller, S.B. and Walker, A.S., 1996. Aerial triangulation - automation ups productivity! Surveying World: Vol. 4, No. 2, pp. 23-25.

Miller, S.B., Walker, A.S. and Walsh, M.C., 1995. Digital photogrammetry at the Ordnance Survey of Ireland. In: 1995 ASPRS/ACSM Annual Convention & Exposition, Technical Papers, Charlotte, North Carolina, Vol. 2, pp. 195-204.

Nale, D., 1995. Digital orthophotography: how accurate is it. LIS/GIS '95, Nashville, Tennessee, 14-16 November, 5 pp.

Nolette, C., Gagnon, P.A. and Agnard, J.P., 1992. The DVP: design, operation and performance. Photogrammetric Engineering & Remote Sensing, Vol. 58, No. 1, pp. 65-69.

Norvelle, F.R., 1994. Using iterative orthophoto refinements to generate and correct digital elevation models (DEM's). In: Proceedings, Mapping and Remote Sensing Tools for the 21st Century, August 26-29, 1994, Washington, D.C., pp. 134-142.

Nwosu, A.G., 1996. Digital versus analytical: a matter of photogrammetric coexistance [*sic*]. Geomatics Info Magazine, Vol. 10, No. 1, pp. 35-36.

Petrie, G., 1983. The philosophy of digital and analytical photogrammetric systems. Zeiss Photogrammetric Week, Stuttgart, 28 pp.

Petrie, G., 1990. Developments in analytical instrumentation. ISPRS Journal of Photogrammetry and Remote Sensing, Vol. 45, No. 2, pp. 61-89.

Petrie, G., 1992. Trends in analytical instrumentation. ITC Journal, No. 1992-4, pp. 364-382.

Sarjakoski, T., 1981. Concept of a completely digital stereoplotter. The Photogrammetric Journal of Finland, Vol. 8, No. 2, pp. 95-100.

Schenk, A. and Toth, C., 1992. Conceptual issues of softcopy photogrammetric workstations. Photogrammetric Engineering & Remote Sensing, Vol . 58, No. 1, pp. 101-110.

Simmons, G., 1996. Missile guidance for the photogrammetrist! Surveying World, Vol. 4, No. 2, pp. 30-32.

Trinder, J. and Donnelly, B., 1996. Digital photogrammetry: what it can do and how it will affect the future of photogrammetry. Geomatics Info Magazine, Vol. 10, No. 1, pp. 6-8.

Walker, A.S., 1995. Analogue, analytical and digital photogrammetric workstations: practical investigations of performance. The Photogrammetric Record, Vol. 15, No. 85, pp. 17-25.