

Trends in analytical instrumentation

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ABSTRACT

This paper describes current trends in the development of analytical photogrammetric instrumentation, now that the classical analogue stereoplottling instruments and stereocomparators have disappeared from the marketplace. Of particular note has been the development of a large number of inexpensive instruments, mainly from small specialist companies, which are often of a quite innovative design. Four distinctive types of such instruments are identified and discussed: those based (1) on scanning mirror stereoscopes and (2) optical transfer instruments; (3) those utilizing small-format photographs and designed principally for use in close-range photogrammetry; and (4) conversions of existing analogue instruments into analytical plotters.

The larger, more expensive and more accurate analytical instruments from the major photogrammetric system suppliers are also analyzed under the headings of their algorithmic approaches and related mechanical and optical design characteristics, the measuring/positioning elements used in these instruments and their computational arrangements. A further detailed discussion of the impact of graphics displays and workstations on analytical plotter design is given, including the development and incorporation of superimposition and stereo superimposition as integral features of these instruments. In contrast with these dynamic developments in analytical plotter design, the area of analytically-based orthophoto printers has seen little new development in recent years.

The final part of the paper deals with digital image correlation and its impact on analytical instrumentation. While it has had a long-standing application to analytical plotters for orthophoto production and DTM data acquisition, the most innovative development in recent years has been the design and construction of highly automated monocomparators. These instruments are now being used extensively in industrial applications of photogrammetry where the target point positions are known or highly predictable, as well as the more familiar area of analytical aerial triangulation.

The concluding remarks cover the probable replacement of current analytical photogrammetric instrumentation by all-digital instrumentation in the future and the difficulties of applying analytical instrumentation to solve mapping problems in developing countries.

Over the last three or four years, and apparently quite suddenly, the classical instrumentation comprising stereocomparators and analogue stereoplottling machines that have been the mainstay of photogrammetry since the 1920s have disappeared completely from the marketplace, to be replaced by the analytical plotter. Of course, the analytical plotter itself is no longer a new idea, the first instruments, the AP1 and AP2 machines, having been built 30 years ago. This immediately begs the question as to why, only now and quite suddenly, does it dominate the photogrammetric marketplace, when for so long it was to be found mainly in the area of military mapping and intelligence gathering? While other factors have played a part, the main reason that the time of the analytical plotter has come is the enormous and rapid development that has taken place in computer technology since

Helava first set out the basic concept of the analytical plotter in 1957/58.

At that time, computers were large, power-hungry, clumsy to use and difficult to program, while the peripherals such as graphics screens that are now taken for granted were expensive and little developed in terms of resolution and speed of operation. To obtain the computational speeds necessary to ensure that an analytical plotter could function like its analogue equivalent meant that special real-time computers had to be designed, constructed and operated specifically for use with analytical plotters. By present-day price/performance standards, they were very expensive, crude and slow, with tiny amounts of memory (RAM) and backing store (*eg*, on hard disk), but they did ensure that the basic concept of the analytical plotter was implemented and proven, even though its use was limited mostly to the military domain. In the mid-1970s, with the advent of small, fast and reliable general-purpose minicomputers, such as the DEC PDP-11, Data General Nova and Hewlett-Packard HP1000, the situation changed radically, and at the ISP congress in Helsinki in 1976 several major manufacturers introduced analytical plotters in their ranges of products.

Since then, the situation has changed rapidly, with the change first to desk-top computers to drive analytical plotters in the early 1980s. The final blow to the analogue instruments has come with the development of powerful low-cost microcomputers on the one hand, and sophisticated and ever more powerful graphics workstations on the other [39]. The former has helped to trigger the development of relatively inexpensive analytical instruments, often of an innovative nature, while the explosive development and growth in the availability of high-performance graphics workstations has resulted in the implementation of concepts such as superimposition and stereosuperimposition which, in practical terms, were virtually impossible to realize before their introduction.

INEXPENSIVE ANALYTICAL INSTRUMENTATION

The word "inexpensive" is of course an emotive one: many potential users in the developing countries or among environmental field scientists, who would dearly like to make use of the new analytical instruments, would argue that they are by no means inexpensive. But comparing them with past and present mainstream analytical plotters, they are inexpensive—if not cheap. A figure of UK£ 25,000 to £ 30,000 may be taken as the upper limit of this class of instrument.

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Analyzing the current trends in their development, we can discern four distinctive types of instrument:

- (1) those based on the use of scanning mirror stereoscopes to provide the measuring/viewing/scanning mechanisms of the analytical instrument
- (2) those that have their origins in the optical transfer type of instrument, allowing simultaneous viewing of a photographic or scanner image and a hard-copy map
- (3) those that accommodate small-format photographs which are intended principally for use in the field of close-range photogrammetry and
- (4) those that are conversions of existing analogue stereoplotting machines and have become fully-fledged analytical plotters.

Without exception, all of these inexpensive instruments are driven by the ubiquitous IBM-PC micro-computer or its clones.

INSTRUMENTS BASED ON SCANNING MIRROR STEREO-SCOPES

It has been extremely interesting to note the developments which have taken place in this area. The mirror stereoscope equipped with binocular viewing optics and mounted on a parallel guidance movement is the traditional instrument of the photo interpreter. To this simple instrument could be added a parallax bar to allow the measurements of x-parallaxes and the subsequent determination of height. A typical product was the Zeiss Oberkochen Stereopret from which the Stereotope approximate instrument was later developed. Next, by stripping out the mechanical analogue computers of the Stereotope, fitting encoders to generate the measured x, y and px values in digital form, and attaching a Hewlett Packard 9800 series programmable desk-top calculator to allow rapid and convenient computations of the heights from the parallax readings, the Stereocord G2 instrument resulted.

System suppliers then realized that exactly the same rather simple hardware could be used to implement an exact analytically-based solution to give accurate model (X,Y,Z) and terrain coordinates (E,N,H) instead of only heights. So a definite trend in the 1980s was the implementation of the image space plotter (Figure 1) concept of Forrest [19], which had previously lain dormant for so long. An obvious example is the Stereocord G3 [44] attached first to an HP-85 desktop computer and now to an IBM-PC clone (Figure 2). Obviously the measurement of plan detail and heights can be carried out only on a point-by-point basis on this instrument. Without an oriented model, the continuous measurement or plotting of plan detail or contours is not possible, though contours can



FIGURE 2 Zeiss Stereocord G3-PC

be interpolated and plotted later as an off-line operation if a suitable contouring program is available.

That there appears to be a strong interest in this area among field scientists, planners and military personnel is evidenced by both the steady sales of the Stereocord G3 and the advent in 1988 of two rival instruments—the Galileo Stereobit and the Topcon PD-1000 Stereotizer—which essentially implemented the same concept as the G3. It seems that the reduced cost of ownership and operation is the decisive factor in the acceptance of this type of analytical instrument, offsetting the lack of an oriented, parallax-free model, which would trouble the photogrammetrist engaged in systematic topographic mapping. It would be fair to say that the development of this type of image space plotter sounded the death knell to the traditional type of third-order or approximate instrument such as the Zeiss Oberkochen Stereotope, Galileo Stereomicrometer and Cartographic Engineering CP-1, which have not been produced for some time.

Achieving a full-blown analytical plotter using the same basic hardware and software as the image space plotter has required only a small step forward via the provision of feedback and control signals and small motors controlled by the PC (Figure 3). This was achieved first by the Autometric APPS IV instrument [24], then by the AP-190 instrument (Figure 4), which is based on Cartographic Engineering's scanning mirror stereoscope [11, 12], and by the Topcon PA-1000 and PA-2000 instruments designed by Goudswaard [23] of ITC and first shown at the ISPRS

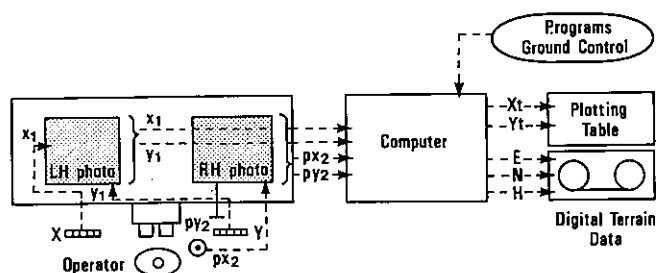


FIGURE 1 Image space plotter

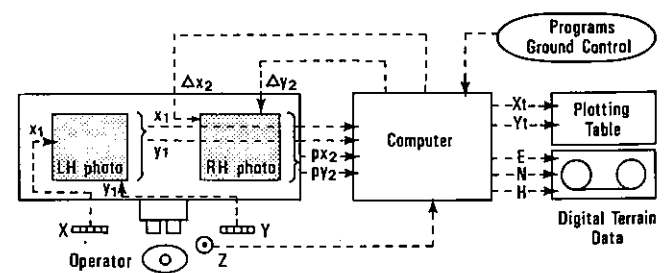


FIGURE 3 Analytical plotter with image coordinates primary

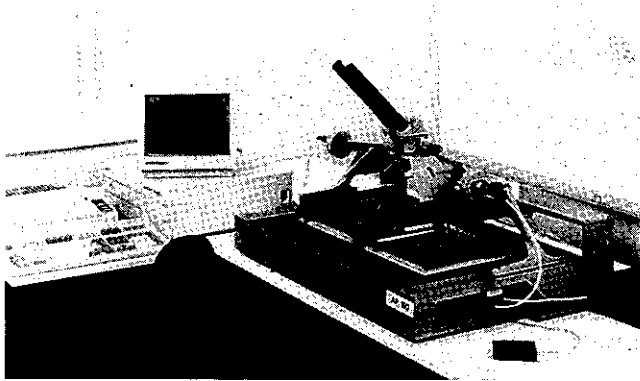


FIGURE 4 Carto Instruments AP 190

Kyoto congress in 1988. Since its introduction, the price of the Carto Instruments AP-190 has actually been substantially lower than that of the Stereocord G3, so it has certainly been a matter for conjecture as to why the two major manufacturers, Zeiss Oberkochen and Galileo, involved in this area had not made the relatively minor modifications to their Stereocord and Stereobit instruments to realize the same type of product, so eliminating the obvious limitations of the image space plotter solution.

In 1992, it has been most interesting to observe how this matter has been resolved. Galileo has indeed made these modifications to produce the Stereobit 20 and 20Z instruments as full-blown analytical plotters. The former model (20) utilizes the mirror stereoscope arrangement of the original Stereobit, while the latter model (20Z) is based on the use of a Nikon stereomicroscope head that offers zoom magnification. As will be seen below, the algorithmic solution is essentially similar to that of the Galileo Digicart 20. With regard to the Zeiss Oberkochen Stereocord, the solution has been to replace the expensive Stereocord with the less expensive Visopret produced by Zeiss Jena. Like the Stereobit, it is available either using a mirror stereoscope with fixed magnification as the observational system or utilizing a zoom optical head (Visopret 10 DIG and 20 DIG). In terms of functionality, however, it remains an image space plotter with point-by-point measurement and plotting of the detail present on the stereopair using the V-CAP software.

That there is a market for this relatively cheap and cheerful exact solution with a fully-oriented stereomodel is shown by the sale of more than 30 AP-190s over a three-year period, mostly to customers in North America and Scandinavia. Many of these are concerned with mapping for forestry purposes; for example, the U.S. Forest Service has purchased 11 of these instruments for this purpose [41]. The Topcon PA-2000 instrument (Figure 5) is intended for sale to both mapping agencies as a production instrument and educational establishments as a training instrument. The production instrument is available in two forms: model PA-2000A with a powered movement of the photocarrier operated via a double keyboard and model PA-2000M in which the x,y carrier movement is made manually. In the training instrument (model PA-2000W), dual sets of oculars are supplied for the simultaneous viewing of the stereo-



FIGURE 5 Topcon PA 2000 (training version)

model by a student and his instructor, and will be accompanied by a set of materials and exercises developed as a special instructional package prepared by ITC [36]. This development is aimed specifically at providing a low-cost entry to analytical instrumentation that could be purchased by mapping organizations and educational institutes in developing (Third World) countries in line with ITC's mission.

The progression in this development of the scanning mirror stereoscope into these various forms of inexpensive analytical instrument is shown in Table 1 below.

It will be noted that the algorithmic approach adopted in all the analytical instruments based on the use of a scanning mirror stereoscope moving pairs of photographs simultaneously utilizes image coordinates as the primary input to the computational solution.

INSTRUMENTS BASED ON OPTICAL TRANSFER DEVICES

The classical optical transfer instruments are the Zoom Transfer Scope (ZTS) and the Stereo ZTS of Bausch and Lomb, designed for the simultaneous viewing of a hard-copy map and either individual images or stereopairs with a view to revising a topographic base map or plotting on the map specialized thematic information interpreted from the photographs or scanner images.

It has been very interesting to observe the steady development of this idea (Figure 6) into a special form of analytical plotter. From the original ZTS has come the Stereo ZTS of Bausch and Lomb and the Stereo Facet Plotter from OMI, later to be transformed into the OMI Automated Stereo Facet Plotter and finally into the APY analytical instrument. The driving force behind much of this later development has been Henk Yzerman, who has steadily pursued the development of the concept, first with Bausch and Lomb, then with OMI and finally with his own company, Photogrammetric Systems APY.

The original ZTS instrument—with its binocular monoscopic viewing, its beam splitter to merge map and photo images, zoom optics to equalize the respective scales, an anamorphic lens to change the photo scale in one direction relative to the other to correct for relief and tilt displacements, and a rotational prism to select the direction—first appeared in 1971 at the ASP/ACSM fall meeting. A developed version, model

TABLE 1 Analytical instruments based on scanning mirror stereoscopes

	Scanning mirror stereoscope	Instrument Type Image space plotter	Analytical plotter
<i>Characteristics</i>			
Input coords	x_1, y_1, px_2	x_1, y_1, px_2, py_2	x_1, y_1, px_2, py_2
Algorithmic approach coords	Parallax equation	Collinearity eq (image coords (primary))	Collinearity eq (image (primary))
Feedback approach	None	None	Implemented
Oriented model	No	No	Yes
<i>Manufacturer</i>			
Autometrics (USA)	APPS I	-	APPS IV
Carto Instruments (Norway/UK)	Carson Image Plotter	-	AP 190
Galileo (Italy)		Stereobit	Stereobit 20/20Z
Topcon (Japan)	-	Stereotizer PD 1000	PA 1000/2000
Zeiss Oberkochen	Stereocord G2	Stereocord G3	-
Zeiss Jena (Germany)	Visopret	Visopret 10/20 DIG	

ZT4-H, equipped with a transparent horizontal stage for the photos is shown in Figure 7A.

The OMI Stereo Facet Plotter (Figure 7B) then extended this basic arrangement to include stereoscopic viewing with additional optical devices to give improved correspondence between photo and map. The OMI Automated Stereo Facet Plotter (Figure 7C) then introduced automatic microprocessor-controlled elimination of x and y parallaxes between the photograph and the map. The final development of this idea (Figure 7D) is the APY analytical instrument [54, 55] where the basic inputs to the PC are the X,Y coordinates given by the cursor of the tablet digitizer (Figure 8) on which the hard-copy map is mounted, supplemented by the height (Z) value given by a separate control on the cursor. The computer (PC) is programmed to provide four output signals in real

time to rotate the plane parallel plates situated in the optical viewing channels for each photograph. These produce displacements of the two images in both the x and y directions to maintain an oriented stereomodel. The computer also plots the measured digital data on a small high-resolution graphics display screen. A three-way superimposition allows the simultaneous viewing of the original map, the stereomodel and the graphics display screen using beam splitter and beam uniter elements (Figure 7D).

The final result is an analytical instrument which is optimized for digital map revision, a task which is now at the top of the agenda for many national mapping agencies and environmental scientists working in conservation bodies and in agencies such as soil, vegetation and geologic survey organizations that provide specialized thematic maps and are now adopting GIS techniques. That at the very least there is a market for such instruments in both the developed world and the developing countries is shown by the sales of 30 APY instruments in Europe (UK, Ireland, Belgium, Germany, Switzerland, Austria and Yugoslavia) and elsewhere (China, Sri Lanka, Pakistan and Nigeria) over the last three or four years. In particular, the Survey of Pakistan has acquired nine APY units which are being used to revise the national 1:50,000 scale topographic map series.

The Bausch and Lomb side of this story has also continued to be developed. The additional analytical capability is contained in the so-called VM module which can be retrofitted to existing Stereo ZTS instruments [31]. The additional hardware components include a pair of illuminated floating marks on plastic disks, which together comprise a parallax bar and which are motor-driven in the x and y directions. Another pair of motors allows the differential movement of one photograph relative to the other (*ie*, px and py parallax movements) under joystick control.

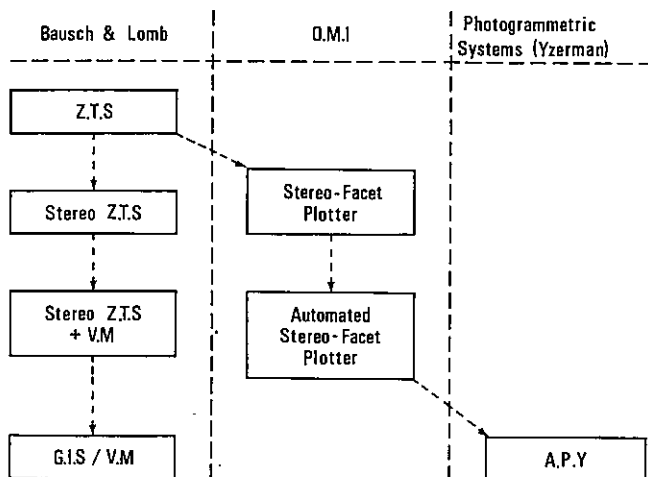


FIGURE 6 Block diagram showing development from ZTS to GIS/VM and APY



FIGURE 7A Bausch and Lomb ZT-4H

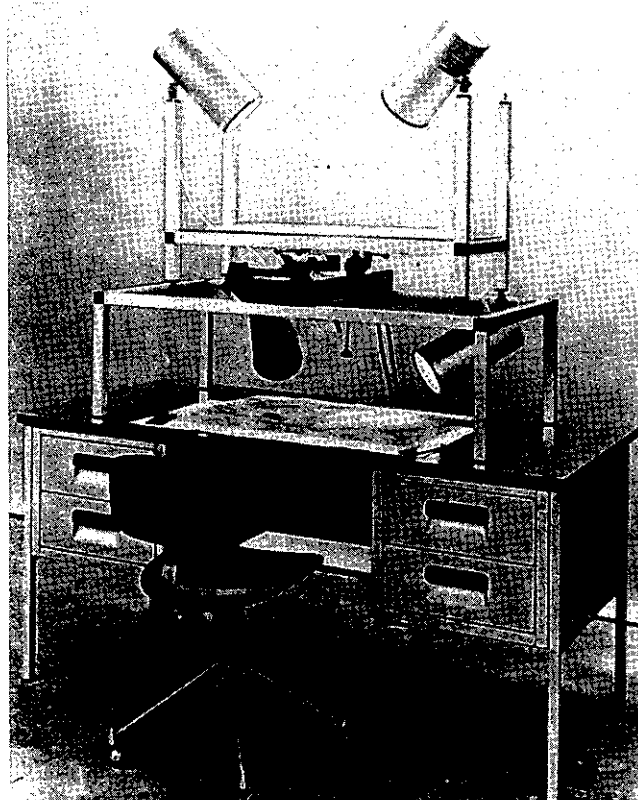


FIGURE 7B OMI stereo facet plotter

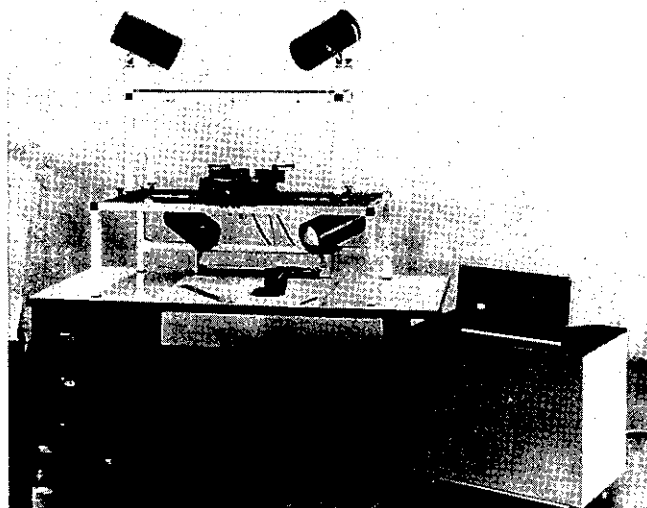


FIGURE 7C OMI automated stereo facet plotter

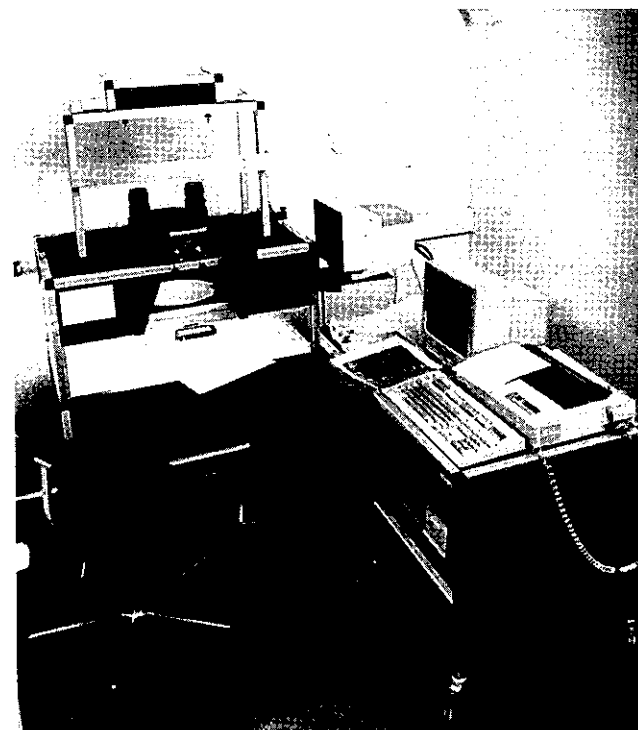


FIGURE 7D Yzerman APY plotter

All four axes are encoded to give x_1 , y_1 , px_2 and py_2 coordinate values to the controlling Intel 8051 microprocessor which is programmed to carry out relative and absolute orientation. Once established, these orientation parameters allow the generation of corrections to the computed height values. The prime aim of the VM module is to add the facility to measure terrain elevation values to the existing map transfer capability. While the additional features ensure that the Stereo ZTS has most of the features of an analytical plotter, including an exact solution, feedback control and parallax-free model, the output planimetric coordinates are in the form of x and y photo coordinates. These values, together with the appropriate orientation parameters and control point information, need to be transferred to the separate Bausch and Lomb Resource Measurement System (RMS) for their conversion or transformation into model (X,Y,Z) or terrain (E,N,H) coordinates using an off-line computational operation.

In the most recent development, called the GIS/VM (Figure 9), the whole set of modules (Stereo ZTS,

VM, RMS) has been integrated to form a single unit, the transfer capability allowing simultaneous viewing of the hard-copy map has been eliminated and an on-line graphics display of the digitized data is pro-

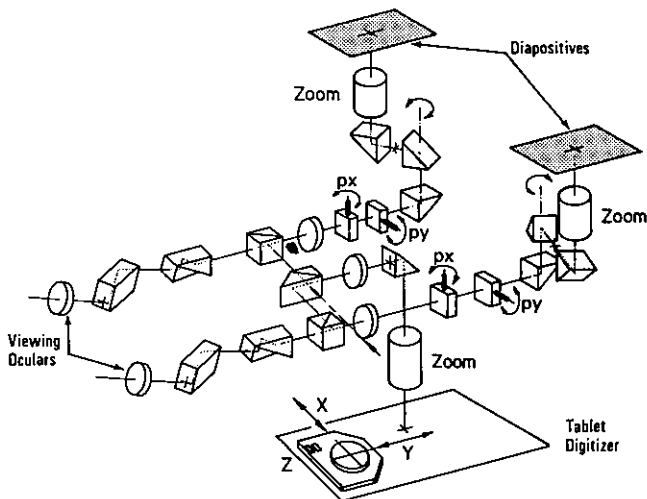


FIGURE 8 APY diagram showing optical components

vided. In this form, the instrument becomes a normal analytical plotter generating three-axis (X,Y,Z or E,N,H) coordinate data for input to a digital mapping, CAD or GIS package. Doubtless the sum total of the Yzerman and Bausch and Lomb (now Image Interpretation Systems) instruments constitutes a very distinctive and potentially very important development in analytical instrumentation, as digital map revision becomes a matter of major concern to mapping organizations.

SMALL-FORMAT ANALYTICAL INSTRUMENTS

The development of specialized lower-cost analytical instruments designed specifically for use with small-format (35 mm and 70 mm) photographs was another quite distinctive trend in development through the 1980s. The starting point can be identified as the HDF-Maco 35/70 instrument designed by Dell Foster [22, 33]. As Figure 10 shows, the solution depends on the input of common x and y movements of the plates generated by a tracker ball to which additional small shifts (Δx_1 , Δx_2 , Δy_1 and Δy_2) are generated as output values by the computer, which also calculates the model (X,Y,Z) and terrain (E,N,H) coordinates. In the original version, this computer was an early type of graphics workstation, the Tektronix 4052 or 4054, but in the latest version marketed by the Zenza Bronica organization (manufacturers of a calibrated single lens reflex camera), this has been replaced by an IBM PC-AT microcomputer.

Since the reduction in format to 6 x 6 cm results in a considerable decrease in the cost of manufacture because of the use of smaller mechanical stages and ways, obviously this is a major consideration to the ever-increasing number of users employing close-range terrestrial photogrammetric techniques or utilizing small-format photographs taken from aircraft. So further instruments have been developed for this specialized market. One of these is the Adam Technology MPS-2 [16, 13], which is a particularly neat solution incorporating an off-the-shelf zoom stereomicroscope as the foundation of its optical viewing system and vertical positioning of the photo stages to reduce the overall size of the instrument.

The Reflex Microscope originally developed by Reflex Measurements Ltd as a high-precision non-contact system for measuring small objects directly without photographs [45], has also been adapted to allow the measurement of stereopairs of photographs up to 6 x 6 cm in size. In this form, it becomes yet another small-format analytical plotter. In place of a single stage plate on which the actual photos to be measured would normally be placed (in the standard form of the Reflex Microscope (Figure 11A)), a plate carrier is provided that has two illuminated stages to backlight the pair of photographs (Figure 11B). Also a beam splitter is attached to the viewing head of the instrument to allow stereoviewing to take place. On the algorithmic side, the instrument follows the object coordinates primary approach with the X,Y values input to a PC via a tracker ball and the Z values via a fingerwheel. The output values from the PC provide signals to four pulsed DC motors. Two of these provide the common x and y movements to both plate carriers (effectively generating the x_1 and y_1 image coordinate values). The other two motors control the Δx_2 and Δy_2 motions to ensure an oriented parallax-free model. Linear encoders allow the positions of the plate carriers to be passed back to the PC that is driving the system.

In contrast to the three small-format instruments discussed above, the Pentax PAMS instrument [48] uses the rather larger 12 x 12 cm format that is likely to be encountered with high-precision close-range terrestrial photography. The impression that both the PAMS and the Maco instruments are aimed specifically at the close-range market is reinforced by the algorithmic solution—the direct linear transformation (DLT) of Karara and Abdel-Aziz with image coordinates primary—which has been implemented in

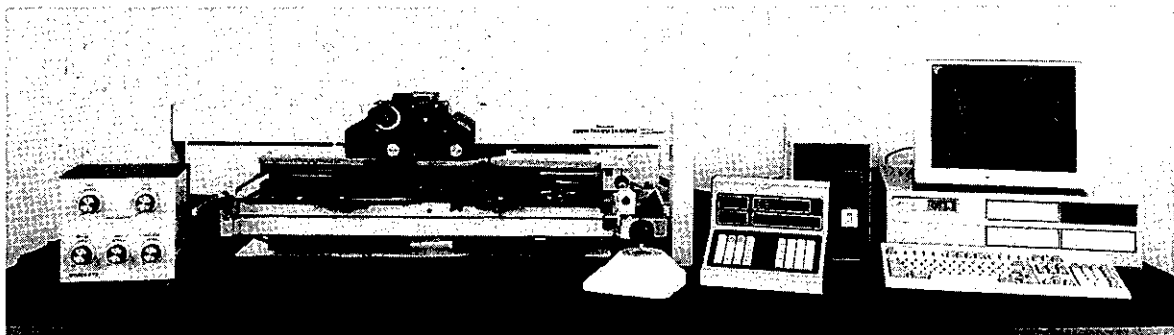


FIGURE 9 Bausch and Lomb (now Image Interpretation Systems) GIS/VM instrument

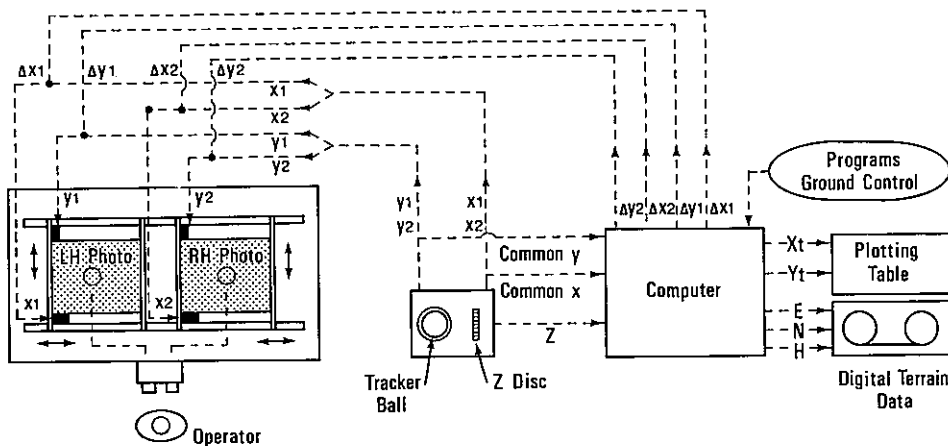


FIGURE 10 Diagram of HDF Maco 35/70

each instrument. By contrast, the MPS-2 and the Reflex Microscope both utilize the classical Helava solution of collinearity equations based on the use of object coordinates as the primary input to the analytical photogrammetric solution.

It is interesting to notice that a small-format image space plotter has also been developed, at least for experimental or research purposes, by Baldwin [2] in the form of his 3D MAPS system which uses the Ross Instruments SFS-3 small-format (10 x 10 cm) stereocomparator as the measuring component of the system. An IBM-PC microcomputer is attached on-line to the stereocomparator to receive its measured

input coordinates (x_1, y_1, px_2, py_2) . The model (X, Y, Z) or terrain (E, N, H) coordinates are computed using the standard collinearity equations, and the output can be displayed graphically on a graphics screen, an HP-7475 drum plotter or a dot-matrix printer. Baldwin has also used a CCD video camera to capture the image of an existing map, which is converted to digital form and displayed on the screen of the IBM-PC. This allows the existing map data transformed to the perspective geometry of the photograph to be compared directly with a digitized version of the photographic image for the purpose of detecting change for map revision.

The obvious conclusion arising from this discussion is that several manufacturers perceive sufficient demand for measuring equipment that can handle small-format photographs to have developed analytically-based photogrammetric instruments specifically for this purpose. It will be very interesting to see if this trend continues; Adam Technology reports the sale of more than 50 MPS-2 instruments to date.

CONVERSIONS OF ANALOGUE MACHINES TO ANALYTICAL PLOTTERS

The conversion of existing analogue stereoplotting machines has been yet another discernible trend of the last two or three years. This has been confined mostly to those lower-cost topographic plotters—such as the Wild B8 or B8S Aviograph, the Kern PG-2

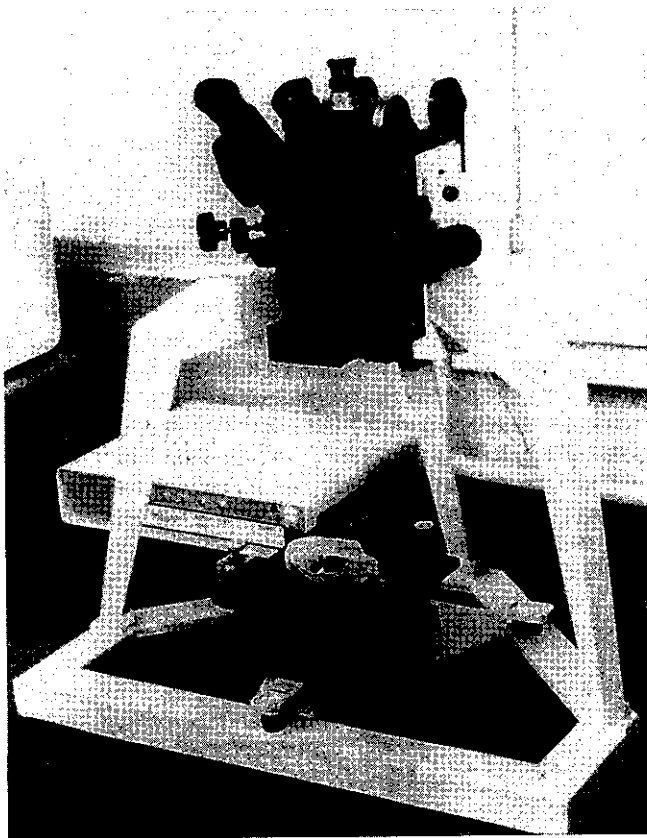


FIGURE 11A Standard form of the Reflex Microscope with single stage plate on which the actual object to be measured is placed

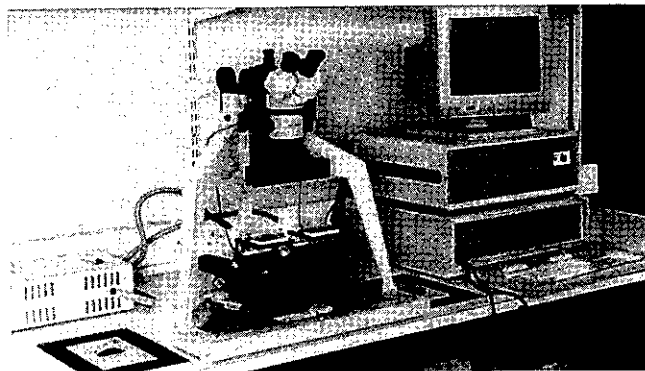


FIGURE 11B Small-format analytical plotter based on the Reflex Microscope and utilizing two illuminated stages to accommodate a stereopair of 6 x 6 cm photographs

and the Zeiss Jena Topocart—which are suitable for such conversions and have been manufactured in very large numbers, thus creating the large potential source of basic instruments that makes it attractive to launch such a venture.

This innovation first got underway with the conversion of several Topocarts into the so-called Anacarts for the U.S. Forest Service by Zeiss Jena's American agents (E Coyote) using mechanical conversion kits, computers (DEC PDP-11s were used originally) and software provided by Helava Associates. No doubt, the lack of an analytical plotter from Zeiss Jena helped to spur this development. But the basic idea has been followed up by two Australian companies—Qasco and Adam Technology—both of which offer conversions of the Topocart, B8 and PG-2. In addition, Qasco is now offering to convert Galileo Stereosimplex IIC instruments. In each case, the space rods or rulers of the mechanical projection system and, in the case of the B8 and PG2, the plotting/tracing device have been discarded, and servo motor drives and linear encoders are fitted to control the four movements, (x_1, y_1, x_2, y_2) of the two stage plates under the control of the microcomputer. The inputs (X,Y,Z object coordinates) to the PC are generated by either joystick controls or X,Y handwheels and a Z footdisk to which encoders are attached (Figure 12A).

In the Adam Technology system, the same microprocessor board is utilized for the real-time solution as is used in the MPS-2 small-format analytical plotter, with the actual PC acting as the main host machine. By contrast, the Qasco QA conversion employs two PCs (Figure 12B): one to act as the control PC, ensuring the correct positioning of the plate carriers and running the software required for both orientation and the capture and coding of digital data; the second, termed the workstation PC, runs the graphics display and the editing/plotting software which can be supplied by Kork Systems, Intergraph (MicroStation), DAT/EM, etc.

SUMMARY

The development of all this lower-cost analytical instrumentation indicates much innovation and ingenuity on the part of many individuals. In total, it constitutes a significant trend and one that can be expected to continue in response to the demands for lower cost of ownership and operation from many users or potential users of photogrammetric equipment. It will be seen that most of these innovative developments have come from either relatively small specialist companies (eg, Carto Instruments, Yzerman, Reflex Measurements, HDF-Maco, Adam Technology, Qasco, etc) or companies that are well-known in the area of field surveying instrument manufacture (eg, Topcon and Pentax) and are now seeking to enter the photogrammetric marketplace. The small specialist companies do not possess the financial resources and the worldwide marketing/servicing networks of the Leica (Wild/Kern) or Zeiss organizations, so that inevitably there will be some worry about customer support, especially at sites located at great distances from the supplier's home base. Such remarks cannot be applied to the two Japanese surveying instru-

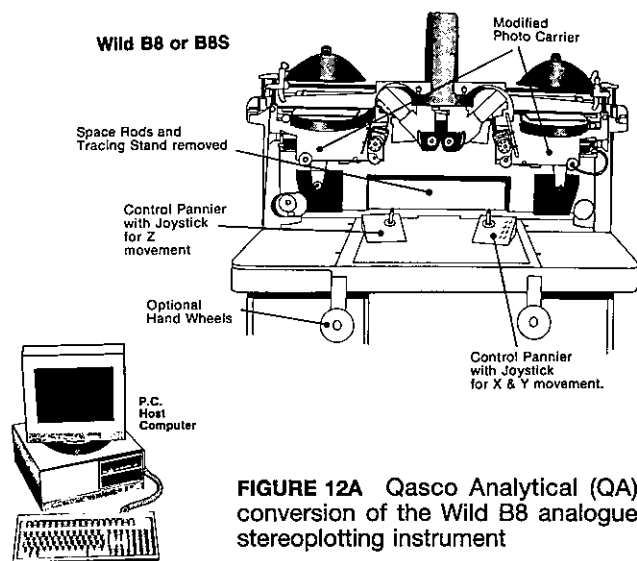


FIGURE 12A Qasco Analytical (QA) conversion of the Wild B8 analogue stereoplotting instrument

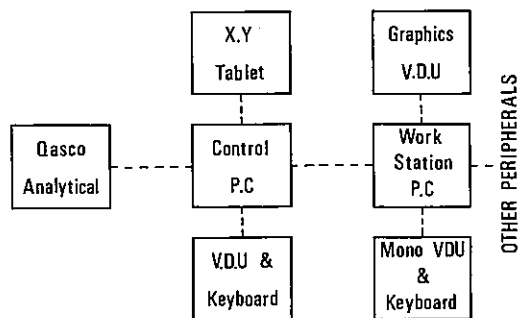


FIGURE 12B Diagram of QA showing the use of twin IBM-PCs

ment manufacturers which have worldwide sales networks. However, the development of their analytical instruments has been quite protracted, so, as yet, they have had little impact on the market.

MAINSTREAM ANALYTICAL PLOTTERS

The use of the word "mainstream" is intended to convey the impression that the instruments described here are those which are recognizably in the mainstream of development by the major photogrammetric system suppliers and are direct descendants of the original OMI/Bendix AP and AS series of analytical plotters with purpose-built, highly accurate measuring stages and control devices and complex optical trains of the highest quality.

ALGORITHMIC APPROACHES AND RELATED MECHANICAL/OPTICAL DESIGN CHARACTERISTICS

In sharp contrast to the vast majority of the lower-cost instruments discussed above, the algorithmic approach used with mainstream analytical plotters is that of object coordinates as the primary input to the computational solution (Figure 13). The exception to the general adoption of the object coordinates primary solution in mainstream plotters is the Galileo Digicart 20 instrument which has been the latest manifestation of the image coordinates primary solution

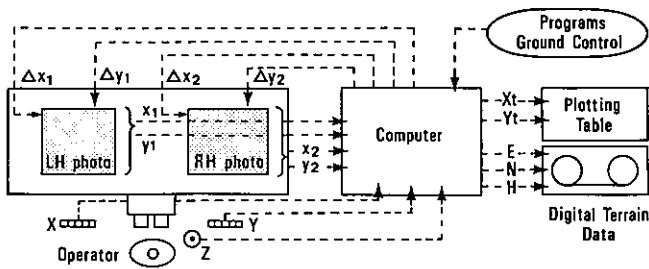


FIGURE 13 Analytical plotter with object coordinates primary

of Inghilleri [28] originally implemented in the Digital Stereocartograph of 1972. Even here, however, Galileo has been forced to develop the Digicart 40 instrument which implements the alternative object coordinates primary solution used by all other major manufacturers. The main reason for this change is (it seems) to overcome the fundamental limitation of the image coordinates primary solution that, in any really practical terms, it is impossible to drive to a specified terrain position under computer control. This can be an important matter in operations such as the measurement of elevations at specific positions as required in data acquisition for digital terrain modeling [40].

As noted previously, the coupled transport of a stereopair of photographs with small differential movements (Δx_2 and Δy_2) of the right hand plate relative to the left is implicit in the scanning mirror stereoscope and in the classical form of stereocomparator. When converted to an analytical plotter with the small differential movements controlled by the computer in real time to ensure a correctly oriented, parallax-free model, an image coordinates primary solution is virtually obligatory. By contrast, the object coordinates primary solution with the plate positions being established by the Δx_1 , Δy_1 and Δx_2 , Δy_2 outputs from the computer requires the use of separate stages and transport movements for each plate. It is this fact that made me [39] observe that the Zeiss Jena Dicometer [47] introduced in 1986—which was the only standard format stereocomparator left on the market—was really intended to act as the basis for an analytical plotter, since it features two quite independent cross slide movements (Figure 14A) coupled together, instead of the common x and y movements of its predecessor, the Stecometer. This assumption was eventually confirmed with the announcement of the Dicomat analytical plotter [3] based on the optical and mechanical elements of the Dicometer and driven by an IBM PC/AT clone microcomputer with two additional microprocessors to carry out the real-time computation and to control the positioning of the plate carriers. This development has not continued, however, since the merger of Zeiss Jena with Zeiss Oberkochen has resulted in the combined company concentrating on the Planicomp series from Oberkochen.

With the virtual demise of the stereocomparator and the slow sales of the few remaining manually controlled and operated monocomparators (the Zeiss Oberkochen PK-1 and Kern MK-2 and CPM-1), and their almost total replacement by high-accuracy ana-

lytical plotters, it is interesting to speculate on the eventual effects of this particular trend on aerial triangulation. Increasingly, it seems, many organizations take advantage of the analytical plotter's capability to generate an oriented model and provide a check on y-parallax elimination to implement aerial triangulation using the independent model method (for which object coordinates are the basic input) rather than the bundle method (for which plate coordinates are the basic input).

Another interesting trend in the mechanical/optical design of analytical plotters is the provision of a capability to accommodate large-format (9 x 18 inches; 23 x 46 cm) photographs through the incorporation of enlarged photostages in their design. This is a matter of special importance in the context of the military mapping, reconnaissance and intelligence gathering operations carried out by western countries utilizing photographs taken by cameras such as the Itek Metritek and its military equivalents. OMI has for long been a main supplier to this market, and its latest offering, the AS-11 PA introduced in 1987, features enlarged photostages as a standard feature. However, the market is obviously large enough to cause the other main photogrammetric system suppliers to modify their existing instruments to accommodate such photographs. Thus Kern offered a version

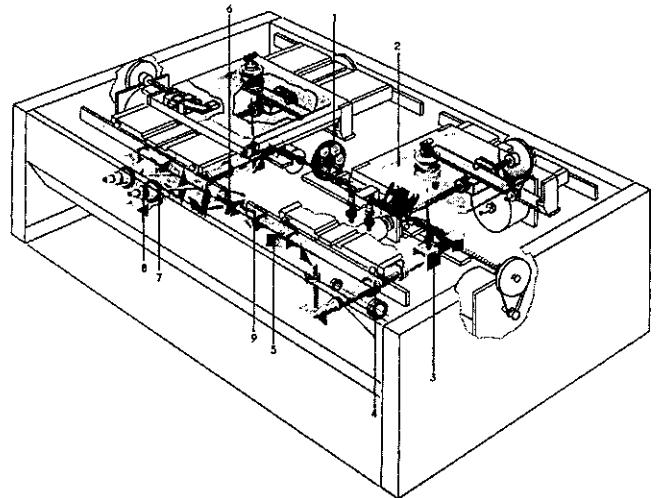


FIGURE 14A Zeiss Jena Dicometer - mechanical construction



FIGURE 14B Zeiss Jena Dicomat

of the DSR 15 (called the model 15-18) which gave the full 25 x 50 cm size required to accommodate such photographs, while the Zeiss Oberkochen P1 Planicomp and Intergraph InterMap Analytic instruments (which share the same optical and mechanical components) offered optional enlarged stages to the size 24 x 33 cm. The Intergraph instrument has been bought in large numbers by U.S. and UK defence mapping agencies.

The U.S. National Ocean Service (NOS) has also for some time been exploiting analytical plotters equipped with enlarged stages, in the form of its NOSAP instrument [21, 46]. It has recently purchased five more instruments of this type—designated PWS-1 (Photogrammetric Work Station)—with a more advanced specification. The optical, mechanical, measuring and control elements of these instruments have again been supplied by OMI (Figure 15), but most of the software has been written in-house to satisfy the special requirements of NOS [15]. In addition to accommodating large-format photographs, the twin enlarged (25 x 50 cm) measuring stages allow four standard format (23 x 23 cm) photographs to be accommodated simultaneously in an individual instrument. This allows multiple stereomodels to be formed and linked up within the instrument with benefit to both aerial triangulation and stereocompilation operations—in the latter case, for example, the user can continue to plot a feature from one stereomodel to the next. The digital coordinate data generated by each instrument are passed to the NOS Integrated Digital Photogrammetric Facility (IDPF) where they are processed and stored in its database.

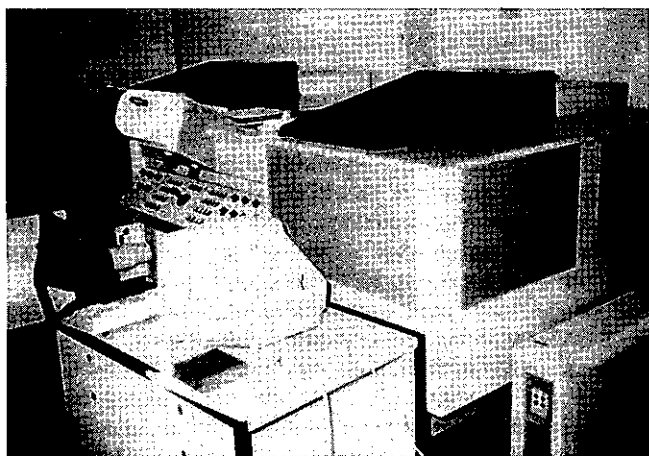


FIGURE 15 The PWS-1 instrument with enlarged photo-stages and multiple model capability developed by the National Ocean Service (NOS)

With regard to the viewing optics of analytical plotters in general, the advances in optical design and manufacture over the last few years have resulted in a clarity and sharpness of detail in most current analytical instruments that would have been inconceivable even 10 years ago. Another definite trend is the incorporation of zoom optics over a wide range of magnifications (typically 6 to 20x) as a standard feature of almost all analytical instruments in this class, instead of the two pairs of interchangeable eyepieces, each with fixed magnification, which was the typical

arrangement in the preceding generation of analytical plotters.

MEASURING/POSITIONING ELEMENTS

As far as the plate positioning systems are concerned, the general trend has been to adopt DC servo motors in a closed loop system, with the positions of the stage plates measured by linear encoders with glass scales and gratings that give a 1 μ m resolution and 2 μ m accuracy. These values are fed back continuously to the control computer. This contrasts strongly with the use of stepping motors and open loop arrangements with no positioning elements in most of the less expensive analytical instruments.

With respect to the object coordinate side which provides the inputs to the algorithmic and computational solutions, increasingly the trend has been to supplement the traditional handwheel/footwheel arrangement used for very accurate tracking, pointing and measurement by adopting fast, free-moving control devices such as tracker balls (used in the Kern DSR 1 and Matra Traster instruments), the freehand device developed by Wild and used in the AC-1 and BC series of instruments, or specially designed cursors used in combination with high-resolution digitizing tablets. This last type of device is used on the Zeiss Oberkochen P1 and P3 Planicoms, where a high-resolution (0.025 mm) digitizing tablet is employed, together with the specially designed P-cursor (Figure 16A) which gives control of the floating mark in the stereomodel with progressive (coarse to fine) speed control of the motion. The P-cursor also incorporates (1) a cross-hair to allow it to be set accurately on specific points on maps or photographic paper prints placed on the tablet, (2) various keys to implement specific operating functions, and (3) a knurled Z-wheel for height measurement. The OMI AP 5 also features a free-moving 18-button cursor (Figure 16B) moving over a high-resolution digitizing tablet for controlling position with a thumb-wheel for Z control, replacing the unique Veltropolo of the early AP/C instruments. Yet another example is the Intergraph InterMap Analytic instrument which features a two-handed cursor with special function buttons built into the back (Figures 16C and D).

COMPUTATIONAL ASPECTS

One of the most basic points to be made about the mainstream analytical plotters is that, over a considerable period, most of these instruments have exhibited very stable design characteristics in respect of their basic mechanical and optical components and measuring elements. On the other hand, the power of their control computers has increased hugely in terms of both processor power and the size of their memory (RAM) and backing-disk storage. Also the availability of high-resolution refresh raster displays has transformed their graphics display and editing capabilities. Thus, for example, the Kern DSR series has changed little in its fundamental mechanical and optical arrangement since its introduction in 1980, while the original DEC PDP-11/03 computer used in the DSR-1 was first upgraded to much more powerful models (11/23 and 11/73) in the PDP series used in the DSR-11 and DSR-12 instruments, and then to still

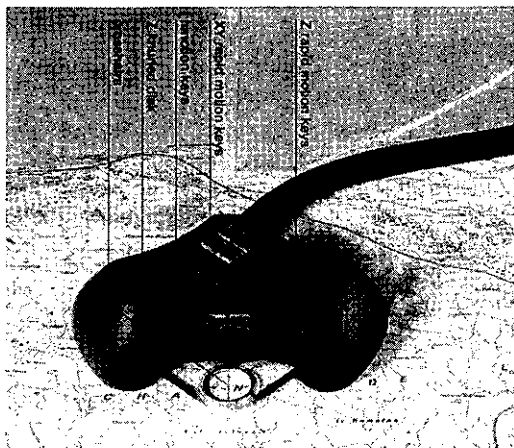


FIGURE 16A P-cursor used in the Zeiss Oberkochen P1 and P3 Planicomp analytical plotters

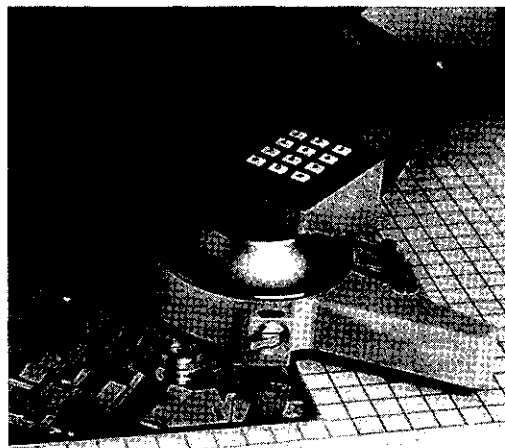


FIGURE 16B Cursor used with the OMI AP5



FIGURE 16C Intergraph InterMap Analytic - two-handed cursor

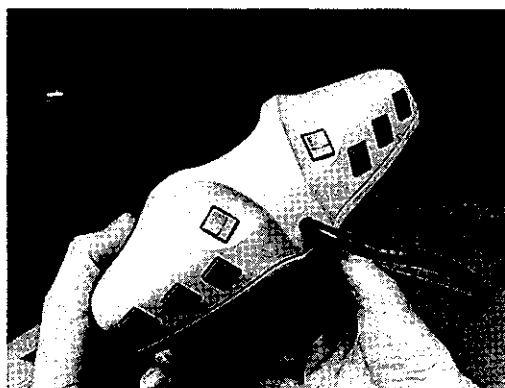


FIGURE 16D Intergraph InterMap Analytic - special buttons on the back of the cursor

faster and more powerful 32-bit processors in the form of the PC-386 used for the DSR-14 and the MicroVAX II or VAXstation used with the DSR-15 instrument. The same remarks can be made of the main series of Planicoms from Zeiss Oberkochen, which from the C-100 model of 1976 through the C-120 and C-130 models of the early 1980s to the P2 model supplied up to 1990 retained the same basic mechanical and optical design with only minor changes, though here the computers have always been from the Hewlett Packard HP-1000 series, albeit with ever faster processors. The Wild BC instruments also exhibited little change from the original BC-1 from 1981 to the BC-3 (whose production has just stopped) in terms of their mechanical and optical arrangements. However, the original Data General Nova minicomputer of the BC-1 was replaced by the Data General DG 30 desktop computer in the BC-2 and this, in turn, was replaced by the 32-bit DG-386 Dasher (an IBM-PC clone) used in the BC-3. Even smaller manufacturers have adopted the same strategy. For example, the Qasco SD-4 introduced at the ISPRS congress in Hamburg in 1980 is now offered as the Adam Technology ASP 2000 with only minor changes in the original optical and mechanical design, but with extensive changes in the electronic control system and a change in the control computer from the PDP-11 minicomputer to an IBM-PC/AT compatible microcomputer [17].

So the general trend is to use proven, well-established

mechanical/optical components in combination with ever faster and more powerful processors, floating point hardware, large amounts of RAM and very large hard disks with short access times. Table 2 summarizes the progression in computer power over the last 15 years for each of these commonly used measuring/viewing platforms from Kern, Wild, Zeiss Oberkochen and OMI.

In this context, it is interesting to note also the use of dedicated microprocessors with programs stored in ROM to solve the collinearity equations, carry out the required transformations and provide signals to the motors that continuously shift the stage plates to their correct positions. In this way, the real-time computation and feedback control are achieved while the main host computer is off-loaded and deals with non-time-dependent computations. This idea was implemented originally by Helava Associates with its US-2 instrument and by Kern with its DSR series. Once the advantages were realized, however, this approach was adopted by numerous other designers, *eg*, in the Zeiss Oberkochen P-series Planicomp instruments with the so-called P-processor [43], the Wild BC-3, the Adam Technology ASP 2000, and the Zeiss Jena Dicomat [3].

It is obvious from the discussion above that, by and large, the mainstream analytical plotters offered by the major manufacturers have been very stable in terms of their mechanical and optical designs, whereas their computational power has been greatly enhanced.