Photogrammetrische Woche 1983
Institut für Photogrammetrie
Schriftenreihe, Heft 9, 1984

THE PHILOSOPHY OF DIGITAL AND ANALYTICAL PHOTOGRAMMETRIC SYSTEMS

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1. Introduction

The intention of this paper is to first explore some of the reasons for adopting digital and analytical systems (-why should photogrammetrists do so?) and then to attempt to assess the exact status of their implementation in practice (- what stage has been reached in the process?). From which it is necessary to outline the main difficulties that have arisen from the adoption of digital and analytical systems (- have the perceived advantages really been achieved?) and then to attempt to predict the future extension of these systems (- where are these developments going and what do they lead to?).

In spite of the title of this paper, the discussion is not intended to be a purely philosophical one. Nevertheless, it is instructive at the outset to attempt to define what digital and analytical photogrammetric systems are, since the terms are used loosely, often implying that they are the synonymous - which they are not. However they do overlap to a considerable extent. Jaksic (1976) has discussed the matter of their definition at some length. As he mentions, the general notion of an analytical instrument or system is an intuitive one. His general definition of an analytical instrument (whether photogrammetric or not) is that it is a finite state digital machine for the real-time addressing of two-dimensional arrays. From this, he defines an analytical photogrammetric instrument as a special case of this general machine with 3 inputs (the model coordinates) and 4 outputs (the plate or image coordinates) capable of addressing 2 two-dimensional arrays. By contrast, the ASP Manual of Photogrammetry concentrates on the mathematical rather than the digital aspects defining the analytical plotter as a digital photogrammetric system which solves the relationship between the photo image coordinates measured in the two-dimensional photo reference system and the ground coordinates in the real three-dimensional world. Citing yet another example, Makarovic, in the published ITC lecture notes, simply defines analytical plotters as digital-type instruments emphasizing that the metric transformation between the model and the corresponding photographs are carried out by a digital computer. Obviously all of these definitions overlap and each has a particular merit: it really depends on where the emphasis is laid.

Leaving aside such theoretical definitions and semantic considerations and taking what is hopefully a more pragmatic viewpoint, it will be apparent that the two terms digital and analytical come together and tend to be used as one mainly in the case of the analytical plotter. However, looking away from this type of instruments or system (as we should call it), it will be seen that it is common also in photogrammetry to use the terms digital data, digital computer, digital processing, etc. (- where the emphasis is placed on digits and numbers and relates to the computational aspects), but to use the expressions analytical methods, analytical triangulation, analytical orientation, etc. (where the emphasis is more on the mathematical and algorithmic side).

At the present time, it will be apparent that there exist digital mapping systems which consist wholly of analogue photogrammetric instruments equipped with digital components (encoders, computers, etc.) and producing digital coordinate data which is processed by a digital computer (Petrie 1981). But such digital systems may include analytical plotters as well as analogue instruments. Indeed in the case of the IPIN system of the Defense Mapping Agency, all the photogrammetric instruments are analytical plotters.

Equally obviously, it is impossible, at the present time, to contemplate an analytical plotter or plotting system which is not based on the use of digital data, digital computers, etc. So while at present the two types of system may be treated as having somewhat different characteristics - e.g. there are digital systems which are not analytical - the integration of the two types of system is fast becoming and accomplished fact and the prospects of this continuing is the theme of the latter part of this paper.

2. The potential benefits of digital and analytical photogrammetric systems

It is instructive to explore the reasons why photogrammetrists should adopt, or have already adopted digital and analytical systems and procedures. In this respect, some or all of the following benefits are assumed to apply:

a) A substantial improvement in accuracy should occur. The resolution of the measuring elements used in comparators, analytical plotters and high precision analogue machines is 1 to 2 µm, while the instrumental accuracy as determined by grid tests is of the order of ± 2 to 5 µm in the plane of the negative. This leads to better accuracy in coordinate determination using actual photographs - typically ± 6 to 8 µm in planimetry (x and y) and ± 0.05 ‰ in height (z). In turn this leads to the use of a larger C-Factor (H/2000 to H/3000) and a discernible economy in the overall mapping process arising from the use of greater flying heights (H). The implementation of digital and analytical systems also allows the possibility of utilising additional (i.e. redundant) measurements and data to further improve the accuracy of the photogrammetric solution.

b) Greater flexibility will result in terms of input to the photogrammetric system. It is possible to ensure in an easy yet rigorous way the correction of systematic errors such as film and lens distortions, Earth's curvature and atmospheric refraction and of non-systematic errors such as assymmetric lens distortions, irregular film displacements, etc. This also leads to an increase in accuracy. Furthermore, with wholly analytical systems, it is possible to make useful photogrammetric measurements.

   i) of photographs taken in unusual attitudes (oblique, convergent, terrestrial, etc.);

   ii) of non-standard photographic images (taken with focal plane shutters, panoramic cameras); and

   iii) of remote sensing imagery (taken by scanners, side-looking radar, etc.).

   The lack of restriction of the focal length of the imaging lens can also be important for some users.

c) A decrease in the time required for orientation is often a result of using computer-based photogrammetric systems. Faster inner, relative and absolute orientation procedures can be implemented and it is possible to make fuller use of additional measurements (redundant data). Furthermore it is much easier to utilise previously determined exterior orientation parameters from aerial triangulation, in-flight recording devices, etc.

d) The automation or partial automation of point-setting also becomes possible in terms of specific image, model or terrain coordinates. Measurements can also be made along pre-determined or pre-defined profile lines and cross-sections or in preprogrammed patterns (square, rectangular, triangular, etc.) for a digital terrain model (DTM).

e) In aerial triangulation in particular it is possible to speed up the process through a decrease in the time required for orientation and model formation and through the possibility of determining the dimensions of the residual errors, model accuracies, model joins, etc. so that the required re-measurement or additional measurement may be carried out while the photographs are still in the measuring instrument.

f) The automatic plotting (drawing) of points, lines, contours, symbols, patterns, etc. is often a much sought-after attribute of a digitally-based photogrammetric system and is coupled to a much larger range and choice of scales than is normally possible with a purely analogue-based system.

g) The generation of data in digital form allows the relatively easy input of photogrammetric data to digital mapping systems and computer-based topographic or geographically-referenced information systems or data banks.

h) All of these points may result in still further benefits being realised in terms of

   i) a decrease in the time required to generate the required data; and

   ii) a lower overall cost in the photogrammetric process itself or in the overall mapping system as a whole e.g. through the elimination of manual draughting and reprographic processes.

3. The extent of implementation of digital and analytical systems and procedures

It is interesting and instructive to review the extent to which the potential or perceived advantages discussed above have actually been realised through the implementation of digital and analytical systems. The situation does of course vary from country to country and even between organisations within a single country.

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However, while making due allowance for this fact and for some fairly strong generalisation, the current situation in the main fields of photogrammetric activity may be summarized as follows:

a) Aerial triangulation is an area where the use of digital and analytically-based systems is almost complete, especially in the more advanced or highly developed countries. Virtually all comparators, analogue stereo-plotting machines and analytical plotters used for this application are equipped with digitized measuring elements and digital recording devices. With the first two types of instrument, there is an ever-increasing attachment and use of inexpensive microcomputers to give assistance with measurement and orientation, to perform checks on model formation and joins, etc. with a view to providing some of the inherent facilities of an analytical plotter. Where analytical plotters have been acquired, they are often dedicated to the aerial triangulation role. Computer-based implementation of block-adjustment is almost universal in larger mapping organisations though with some residual use of simple polynominal strip adjustment in less sophisticated environments, e.g. in smaller government and private mapping agencies in developed countries and in many organisations in poorer developing countries.

b) Stereo-plotting and/or the measurement of DTM's are of course standard tasks in almost all photogrammetric organisations. Analytical plotters are slowly increasing in numbers, though the tendency is to utilise them for aerial triangulation, the generation of DTM's, non-topographic photogrammetry, etc. where their capabilities may be fully exploited, rather than for routine map compilation. Generally speaking, in most organisations, analogue stereo-plotting machines still provide the main capability of specific and clearly defined tasks such as the plotting of topographic maps from near-vertical, wide-angle, aerial photography. Increasingly, however, in the more advanced countries, the demands from engineers, architects, planners, administrators, lawyers, etc. who make use of computer-based design systems and information systems as well as the needs of the survey organisations themselves to implement digitally-based mapping systems have led to these analogue instruments being equipped with devices to generate and record numerical coordinate information in digital form. These may be relatively simple and inexpensive - e.g. sufficient to carry out blind digitizing or they may be quite sophisticated and expensive as when they are attached on-line to micro- or mini-computer systems to provide the photogrammetrist with assistance via prompts, error detection and flagging, inter-active displays and editing of digitized data, etc. Very many such systems have appeared in North America and Western Europe. On the other hand in many organisations there is at present a poor interface of these digitally-based photogrammetric systems with the cartographic stages which follow them in the mapping process. Traditional drawing and reproduction methods still reign but presumably must decline in importance with the introduction of less expensive computer-driven film output devices. The technology exists but is still greatly under-exploited. With the increasing awareness of and probable advent of digital image processing, the situation must surely change.

c) Orthophotograph production provides a varied and sometimes confusing scene. At the one end of the scale, the use of simple, efficient optical projection and optical transfer devices attached to analogue stero-plotting machines is still widespread. At the middle level, the development of sophisticated computer-controlled orthophoto devices such as the Zeiss Oberkochen Orthocomp, Wild OR-1 Avioplan and OMI OP/C-2 has ensured that instrumentation exists which will fit into a digital and analytical environment irrespective of whether analogue or analytical stereoplotters are used for the measurement phase. At the top end of the scale (in terms of sophistication and expense) the development and use of highly automated analytical plotters such as the Hobrough Gestalt GPM-2 and Bendix-OMI AS-11-BX equipped with correlation devices and optimised for orthophoto production probably represents the highest level and the most thorough implementation of digital and analytical systems achieved to date in photogrammetry.

4. The difficulties encountered with digital and analytical systems

The benefits likely to arise from the adoption of digital and analytical systems and procedures have been set out in section 1 of this paper and will have been experienced to a greater or lesser degree by those photogrammetrists who have implemented them. Simultaneously a number of difficulties will almost certainly have been experienced too. These may include some of the following:

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a) The considerable financial investment required for the hardware and software of a digital or analytical system may simply not be available in the case of smaller organisations in developed countries and most surveying and mapping agencies in poorer, less well developed nations.

b) There is a need for a minimum level of technical knowledge and of economic development before digital/analytically-based photogrammetric systems can realistically be contemplated or be implemented in practice. Lack of knowledge can be a major drawback - many organisations in developing countries do not have the cadre of experts in analytical photogrammetry, computer programming and systems, electronics, etc. necessary to implement digital and analytical systems. Reliance on foreign experts may be disadvantageous. Elementary matters like the chronic unreliability of mains electrical supplies, the unavailability of spares, lack of foreign currency, poor servicing facilities, distance from manufacturers etc. all become items of great concern to anyone trying to implement high technology systems in many developing countries.

c) The consequences of implementing digital systems on staff and personnel cannot always be foreseen or predicted. There is one national mapping organisation in Europe where a comprehensive highly sophisticated and very expensive digital mapping system lies substantially underused, indeed pretty unused, because of refusals and objections from the staff to implement the new technology and procedures - since they will result in a substantial loss of jobs. In developing countries, the low cost of staff means that the elimination of labour-intensive tasks does not offer the financial benefits which will result in developed countries with high labour costs.

d) The lack of reliability of many of the electronic components and devices - incoders, displays, motors, computers, recording devices, computer peripherals, etc. - which form an integral part of a digital or analytically photogrammetric system - is a matter which receives less public attention than it should. For most photogrammetrists, the reliability which is experienced is an order of magnitude less (i.e. poorer) than that to which we had grown accustomed to in the case of the optical and mechanical projection analogue instruments. This carries with it a substantial financial overhead or penalty in terms of the provision of service personnel and an organisation capable of a rapid response to more frequent calls for repairs, adjustments, etc.

e) While all manufacturers of computer-based photogrammetric systems emphasize their user-friendliness, such claims have to be treated with some scepticism by those photogrammetrists who have to operate or implement these systems. Even the best designed are often inflexible in many areas requiring adherence to a predetermined sequence of operations which constrains the use of the system. At present, we are far from providing systems which are efficient and comfortable from the operational point of view. Routines for the detection and correlation of blunders and errors need to be improved. Many systems, indeed most, are intolerant of errors in procedure or measurement on the part of operators and, in particular, it is often difficult to recover from such errors without considerable loss of time due to the need to backtrack and repeat input sequences and measurements already carried out at an earlier stage of the procedure. A further consequence of this inflexibility is the need for expensive inter-active editing facilities to discover and rectify defects which cannot readily be put right at the photogrammetric stage.

f) Closely allied to the previous point is the basically unforgiving nature of computers with regard to errors in input data, correctness of data format, errors in or corruption of stored data or program statements, restrictions in input/output procedures and devices, etc. While overall flexibility is undoubtedly an inherent and implicit advantage of a digitally-based system, the constraints of the computer hardware and of their operating systems act like a straight jacket as far as the operational side is concerned. The fast-changing situation in respect of computer design leading to rapid obsolescence of hardware including the computer itself and its peripherals also make it much more difficult to achieve a stable and satisfactory operational environment.

g) There is no question that software is the heart of all digital or analytical photogrammetric systems, yet the investment in money and time required on the part of the manufacturer and the mapping organisation itself to produce satisfactory software is vastly under estimated. Documentation becomes a matter of high concern yet is very difficult and expensive to provide - and, even then, may be unsatisfactory in its quality. Furthermore it is extremely difficult for users to alter programs to suit their own particular purposes without having unforeseen and potentially damaging effects on the existing software provided for the system. Alterations to programs can of course be made by the manufacturer or provider of the software, but often at an unacceptably high cost both in financial terms and in consequent loss of time. This is a special problem for smaller mapping organisations. On the other hand if no alternations are made or are possible, the system remains essentially a black box device in that it will operate only in a set sequence and with the limitations imposed by the software supplied with the system.

h) Software incompatability is an accomplished fact especially in the context of analytical plotters. Users are locked into specific computer hardware each with its own unique operating system, compilers, assemblers, etc. and with the specific software designed to utilise the hardware of an individual manufacturer or supplier. While general purpose applications programs such as PAT-M are applicable at a higher level and can be implemented on a wide range of computers, the opposite is true of the programs supplied by instrument manufacturers and systems suppliers.

On analysing all there various difficulties which can and do arise with digital and analytical instruments, it becomes obvious that, apart from the comparative lack of reliability of the electronically-based hardware, most of the difficulties arise either from the economic, financial and social environments within which the systems have to be acquired and operated or they are concerned with software, especially its inadequacies, cost and frequent incompatability. While the former group may be more difficult for the mapping organisation or the suppliers of systems to address or to change, the required improvements to the software are matters to which those photogrammetrists responsible for the design and implementation of digital and analytical systems can definitely address themselves with benefits to everyone concerned.

5. Progress towards all digital and analytical systems

Great progress has been made in implementing digital and analytical photogrammetric systems over the last decade. Eleven years ago at the I.S.P. Congress held in Ottawa, there were only two non-military analytical plotters shown and these had limited performance compared with present day machines. Also they were only a few monocomparators and stereocomparators included in the catalogues of the photogrammetric manufacturers. Simple hard-wired digitizing units were available for comparators and analogue stereo-plotting instruments. Almost all were equipped with slow output devices using punched cards or tape for digital output or hardcopy produced by electric typewriters and teletypewriters. The transformation to the present-day position has been due almost completely to the dramatic far-reaching developments in computer hardware and software that took place in the latter half of the 1970's. The cost of the hardware dropped dramatically, so that general-purpose mini-computers and micro-computers with fast processors; large amounts of main memory; large-capacity peripheral storage devices; fast access and rapid transfer rates between processor, memory and peripherals; etc. became available at prices that were unbelievably low by previous standards. Also computational speeds were so high that even the real-time programs for analytical plotters could be written in higher-level languages, so moving software development out of the domain of specialised and esoteric machine codes and assemblers. The improved efficiency of operating systems, compilers, etc. also contributed greatly to this changed situation, not least in the eyes of the photogrammetrist. The result of all these developments (which in total could certainly be called revolutionary) was a complete change in the perception of devices such as the analytical plotter on the part of the main body of photogrammetrists. While the merits of the basic idea were long recognised, the opinion that the instruments were horrendously expensive and rather clumsy and mainly suited to the solution of the special problems and particular needs of the military intelligence and mapping communities of research institutes was one which was held by almost all photogrammetrists. The period 1975/80 saw a radical change in attitude as the prices of computers and thus of digital computer-based systems tumbled and the accompanying improvement in the ease of use became apparent.

So over a very short period of time, digital and analytical systems and procedures have suddenly become widely accepted, at least in the developed world. It is of course difficult, perhaps foolish, to predict the future but this immediately begs the question as to where we are in this development. Are we just part way along the development of this particular approach? The view can be put forward that the logic of the digital and analytical philosophy points to the adoption of a wholly digital and analytical approach. This is not a totally new concept - the work of Sharp and his associates (1964) at IBM twenty years ago can

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be recalled. In retrospect, that particular development now appears premature. However, has the time and the level of technical development now been reached for this philosophy to be implemented and its potential realised?

i) On the data acquisition side, in spite of the wide dissemination of digital MSS data from Landsat, there is as yet little sign of digital data acquisition being applied to mainstream photogrammetric operations, especially those conducted from aircraft. Film cameras still rule, but are digital data acquisition systems possible and, if so, will they come to pass?

ii) Turning to the photogrammetric hardware and inspecting a block diagram of the construction of a computer-assisted comparator or an analytical plotter (Fig. 1), it is immediately apparent that only the comparator unit with its optical and mechanical components has to be produced by the photogrammetric instrument manufacturer. The rest of the hardware comprising the computer, its disk and tape drives, video terminals, printers, etc. are all obtained from the manufacturers of computers and peripherals. Perhaps even the comparator unit can be replaced by the computer and other digital components.

The possibilities of all-digital solutions to these two areas will now be discussed.

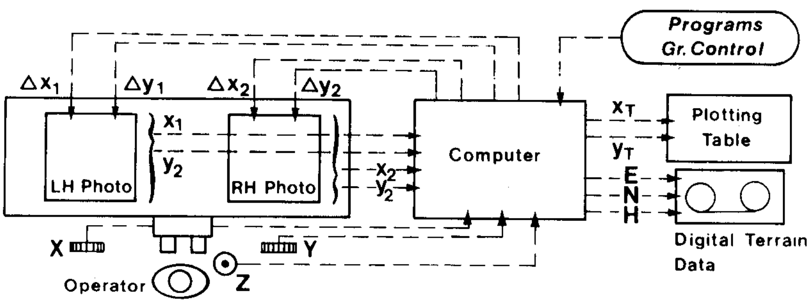

Fig.1 A Computer-controlled analytical plotter.

Pixel Size (μm)	Pixels per Line for 23 cm	Pixels per Image (23x23 cm)	If image is quantized at 8 bits per pixel (bits)
10	23,000	529,000,000	4,232,000,000
20	11,500	132,250,000	1,058,000,000
50	4,600	21,160,000	169,280,000
100	2,300	5,290,000	42,320,000
150	1,533	2,350,089	18,800,712
200	1,150	1,322,500	10,580,000

Table I : Digital Image Data produced from digitizing a metric camera frame photograph (23 x 23 cm format)

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6. All-digital data acquisition

a) Film Cameras

As mentioned above, film cameras reign supreme for image recording at present, giving well-defined and stable metric properties, very high resolution and allowing the storage of the image data in a compact format, any part of which can easily be accessed. It is of course possible to convert the monochrome (black and white) image to digital form using a drum scanner or scanning densitometer. The amount of digital image data which will be generated by this process is shown in Table I. As Helava (1972) has mentioned:

> "From the photogrammetric point of view, the objective of the conversion is to obtain a digital representation of the image data having a spatial accuracy and density resolution commensurate with the requirements of the photogrammetric task at hand. Spatially, the optimum interval for image data sampling will depend on both the image characteristics and the use to be made of the data. There is no point in sampling with a finer quantization than is required to yield the output quality actually required. The optimum sampling rate can be surprisingly low if photographic quality and fidelity of image information is not required to make possible subsequent highly sophisticated image analysis".

All of this can be readily seen by the 100 : 1 reduction in digital data from 529×10^6 pixels to 5.29×10^6 pixels, over the sampling range 10 μm to 100 μm.

b) Scanners

The all-digital imaging technology is at present concentrated on scanners, the alternative approach of using video cameras is exemplified by the Return Beam Vidicon (RBV) cameras of the Landsat series being out of favour at the present time. It is convenient to consider scanners under two headings:

i) those utilising optical-mechanical scanning; and
ii) those using linear arrays operating in the pushbroom mode.

The use of either type of line scanner provides a more extended period of time over which the data can be imaged and recorded, so allowing a single scene or image can be built up sequentially as compared with a film camera where the whole image is recorded simultaneously over a very short period of time (Figs. 2 to 4). The characteristics of four currently representative devices - the Landsat MSS and TM optical-mechanical scanners and the MOMS and SPOT devices using linear arrays are given in Table II. It can be seen that, with these two devices, the total data being generated is of the same order and range as that of a metric frame camera, except where the highest resolutions and smallest pixel sizes are concerned. Moreover the use of the TDI (time-delay and integration) type of CCD areal array in linear fashion to sufficient imaging power at low light levels, has been reported to produce a 10,240 pixel focal plane using five 2048 x 96 element arrays butt joined together. This shows that linear arrays will be quite capable of producing high resolution images of the same order as a metric camera.

The question may be asked as to whether or not an all-digital framing camera with similar characteristics to those of a metric film camera is feasible or not. The advantage of such cameras would be their compatibility with existing photogrammetric principles, procedures and software. The ease of achieving stereo-coverage and the fixed orientation of the whole frame, would be further advantages of such a device as compared with line scanners where the probability of gaps, double imaging and changes in orientation between imaged lines is a major difficulty, particularly with airborne scanners as distinct from satellite-borne scanners such as MSS, TM, MOMS and SPOT which produce their line-scanned images in the near vacuum of space. Such all-digital cameras do already exist using both the optical-mechanical scanning approach and solid-state areal arrays (instead of linear arrays). Examples are:

i) The Barr and Stroud IR-18 infra-red imaging camera (Figs. 5 and 6) which uses high-speed optical-mechanical scanning to provide a broadcast television compatible image. Thus the imaging frame size is 625 x 625 lines = 390,625 pixels, with 50 full frames being exposed per second, amounting to a data collection rate of 19,531,250 pixels per second.

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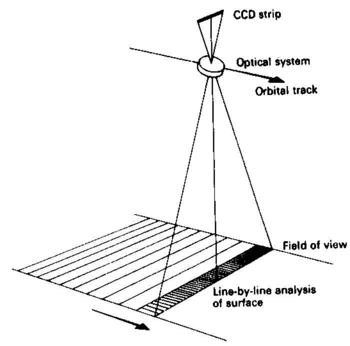

Fig.2 Principle of the Pushbroom Scanner.

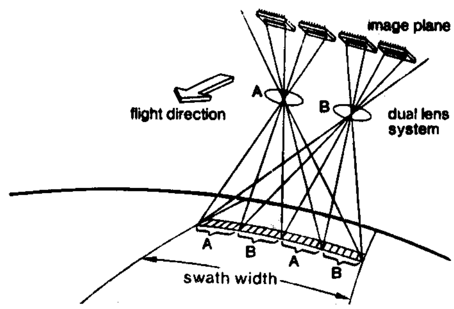

Fig.3 MOMS Dual Lens Pushbroom Scanner.

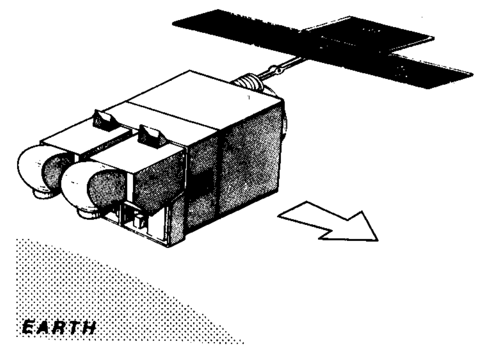

Fig.4 SPOT Satellite with two HRV Pushbroom Scanners.

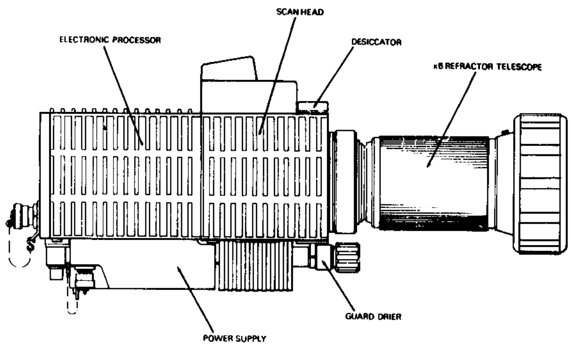

Fig.5 Barr & Stroud IR-18 Mk II Thermal Imaging Camera (Television Compatible).

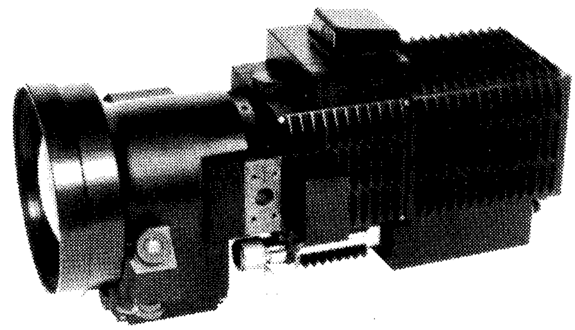

Fig.6 Barr & Stroud IR-18 Mk II Thermal Imaging Camera (λ = 10 µm)

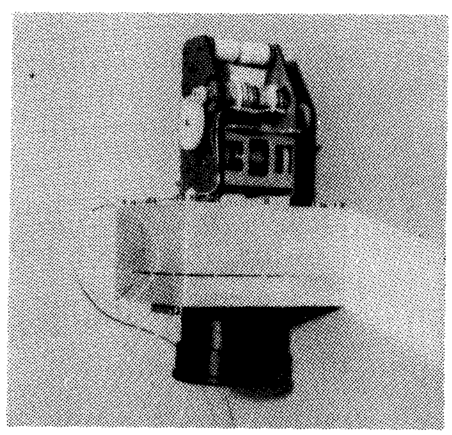

Fig.7 UOSAT Digital Frame Imaging Camera.

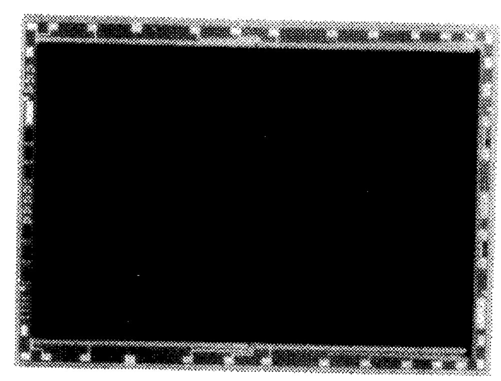

Fig.8 GEC Charged Coupled Device (CCD) Areal Imaging Array for UOSAT Camera.

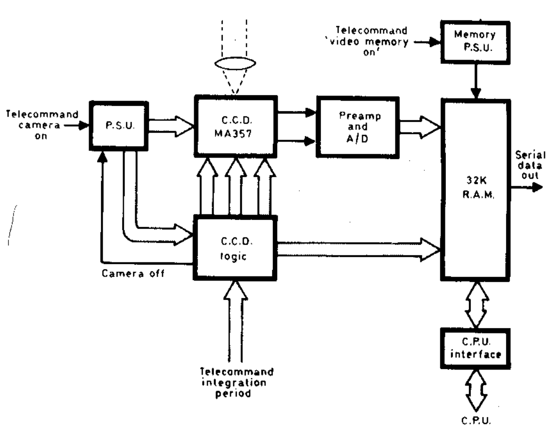

Fig.9 Block Diagram of the UOSAT Digital Frame Camera Imaging System.

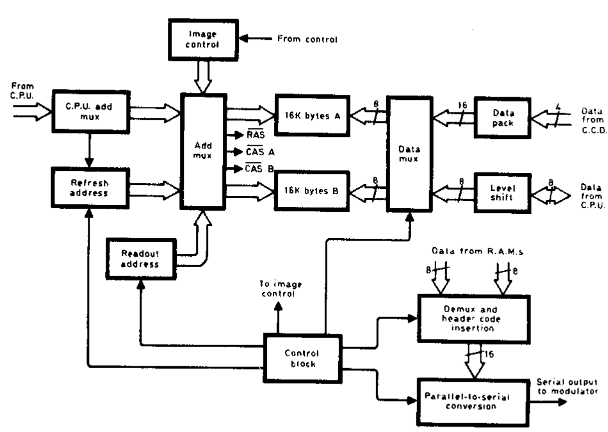

Fig.10 Block Diagram of the UOSAT Digital Frame Camera Video Memory.

ii) The solid-state framing camera orbited in the small UOSAT (OSCAR-9) satellite uses an areal array of CCD's comprising 288 x 385 lines manufactured by GEC in the U.K. (Fig. 7). This produces 110,880 pixels per frame, the low resolution capabilities being made compatible with the limited transmission capabilities of both the satellite and the receiving facilities of amateur radio enthusiasts (Traynor and Jeans, 1982).

In both cases, the compatibility of the image device with standard broadcast television formats, framing rates, etc. is the main consideration. However, solid-state CCD areal arrays of 800 x 800 to 1125 x 1125 lines have been developed for high definition television (HDTV). Apparently it is entirely practicable to mosaic a number of these devices together, in which case, again one would approach the imaging capabilities of a metric camera operating at lower resolutions (50 to 100 µm). Whether the development of an all-digital metric framing camera will be practical from a technical point of view and be economically justified must remain an open question at the present time. Certainly the possibility cannot be ruled out.

c) Digital Storage

Inevitably, the matter of being able to store in digital form the colossal amounts of data generated by airborne and spaceborne imaging systems needs to be discussed. This question has already been addressed in some detail by Konecny (1979) and requires no detailed repetition here. Konecny estimates that a standard 8-track computer-compatible tape (CCT), 720 metres long, can store the image data from 2.5 standard-format (23 x 23 cm) metric photographs digitized with a 25 µm pixel size. On the other hand, a standard 24-track high-density digital tape (HDDT), 2,800 metres long, can store 900 such photographs with a 12.5 pixel size. These will of course be held sequentially as a form of mass storage. Turning to the fast access type of storage device required during actual computer operations, an 88 M byte disk can store the data for a single photograph with a 25 µm size. Larger (300 to 400 M byte) disks are now quite common even on mini-computers used for image processing. Hofmann (1982) made a similar study in the context of the MOMS pushbroom scanner.

It is also worth mentioning the enormous storage capabilities of video tapes and video disks which can be written on inexpensive recorders built in such large numbers both for home and professional use. The analogue data contained on such media is readily converted via frame memories to digital form for computer processing. The video disk (Fig. 11) in particular offers distinct possibilities for the permanent non-eraseable long-term storage of digital image data which is stored as a series of microscopic identations etched into the surface of the disk and may be read either by an electronic stylus (JVC Video High Density system) or by a laser beam (Phillips Laser Vision system) (Fig. 12). The wholly digital equivalent of the video disk which can be interfaced directly to a computer is the new type of glass disk drive which is now being offered by Shugart, and by Control Data (CDC) and Phillips at OEM prices of $ 5.000 to $ 6,000 per drive for storage capacities on a 12 inch removeable glass disk of 1 G byte. Again the data is non-eraseable. The application of this type of technology to the storage of digitized photographic data for photogrammetric applications is obvious.

Finally it is also apparent that random access memory (RAM) is now becoming very inexpensive by previous standards so that very large quantities can readily be incorporated in computers and in other digitally-based devices and can readily be addressed using modern 32 bit super mini-computers. The parallel development of inexpensive frame memories for use with video technology is also of great potential in the development of all-digital photogrammetric systems.

7. All-digital measuring systems

The possibilities of an all-digital measuring system should also be considered. In a sense, this can be regarded as having already arrived in at least one area of photogrammetry in the form of the analytical plotters such as the Hobrough-Gestalt GPM-2 and the OMI Bendix AS-11 B-X devices designed for specifically automatic image correlation and optimised for the generation of orthophotographs and digital terrain models (DTM's) at high production rates. The possibilities of producing orthophotographs digitally by differential rectification, combining digitized photographic data with DTM data have also been outlined by Konecny (1979). However, this still leaves those analytical instruments such as comparators, analytical plotters, etc. which allow an operator to measure discrete point

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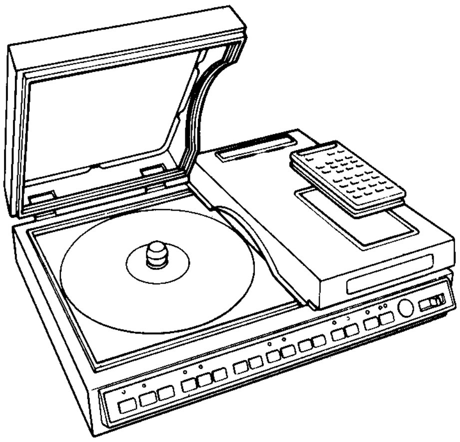

Fig.11 An Interactive Video Disk System Suitable for the Permanent Storage of image data.

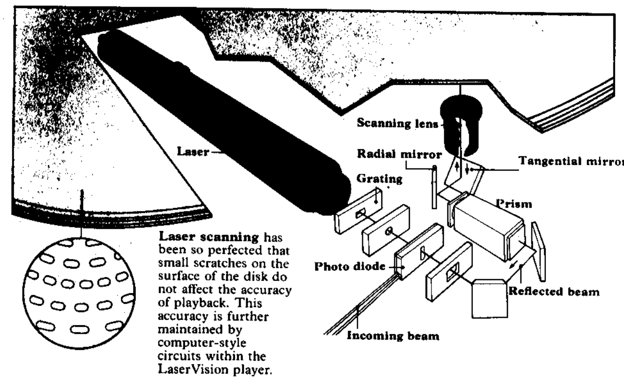

Fig.12 The Phillips Laser Vision Video Disk in which the image data is stored as small bits etched into the reflective surface of the disk and read off with the beam from an He-Ne laser.

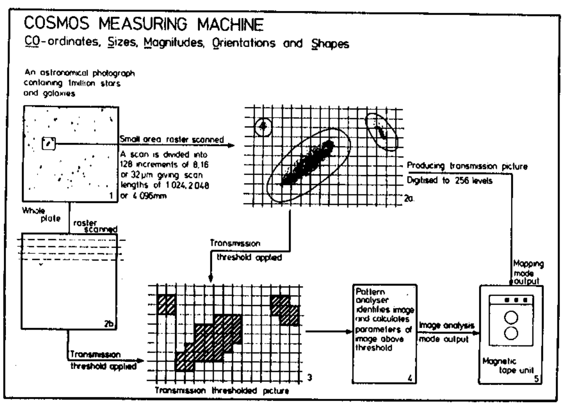

Fig.13 The COSMOS measuring machine used for the automatic measurement of star plates. It has also been used for the digitizing of image data from standard aerial photographs.

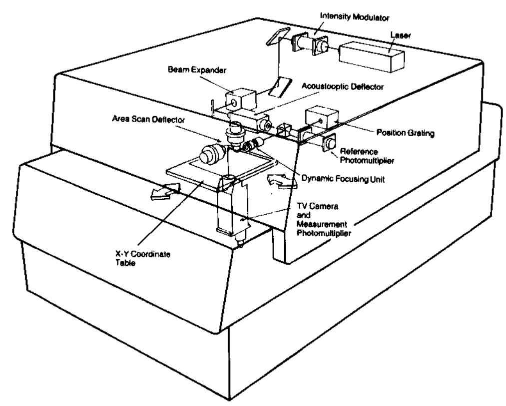

Fig.14 The Automatic Plate Measurement Facility of the University of Cambridge which consists of a precision laser-scanning micro-densitometer connected on-line to a computer.

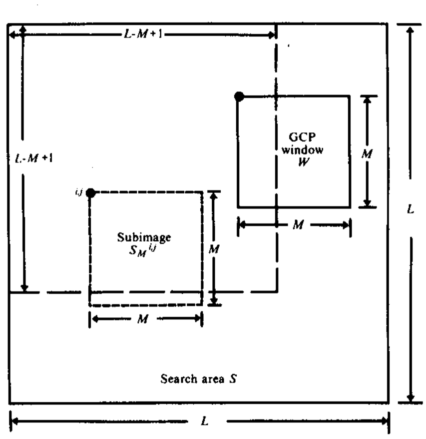

Fig.15 The strategy for the location of Ground Control Points (GCPs) (Bernstein 1976).

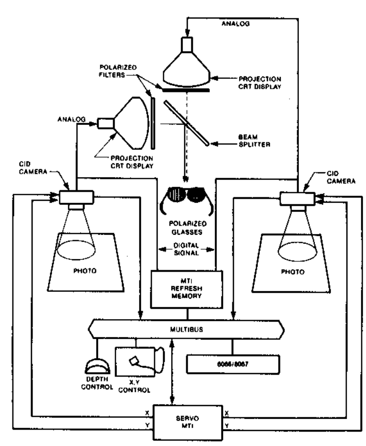

Fig.16 The Matra Video Correlator Compiler (VCC) video/digital system for use in generating 3-D digital coordinate information from a stereo pair of photographs.

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images for aerial triangulation, stereo-plotting, etc. utilising a substantial and expensive optical and mechanical construction besides its digital components. If, however, digital image data is available or can be generated, then it is apparent that photogrammetric measurements of individual point images can be made using digital techniques in a manner and to an accuracy quite commensurate with an analytical system omitting the accurate but expensive comparator unit.

a) Digital Mensuration Techniques

Addressing first the matter of the measuring process itself, one important and relevant point is that the automatic measurement of certain types of point images is becoming an accomplished fact. Such measurements have been made on discrete images on digitized large-format photographs of astronomical plates for some years - the computer-controlled COSMOS measuring machine (Fig. 13) of the Royal Observatory, Edinburgh (ROE) and the Automated Photographic Measuring System (Fig. 14) of the University of Cambridge are representative. These do have a precision comparator unit to support the plate which it is scanned by the integral microdensitometer unit which digitizes the photographic image data but the rest of the system is all digital. The photogrammetric equivalent of these devices is the Automated Reseau Measuring Equipment (ARME) developed for the Defense Mapping Agency (Roos 1975). In spite of the title, the instrument can measure digitally and automatically fiducial marks, reseau crosses, point stellar images (from spaceborne mapping systems) and artificially marked points on photographs. Recently the analysis of measurements of well-defined features (crosses, dots, edges, etc.) on purely digital data by Thurgood and Mikhail has shown that accuracies in pointing in the range 0.02 to 0.06 pixel are possible which, for a 50 μm pixel, corresponds to 1 to 3 μm.

A further development has been the use of ground control points (GCP's) which are stored digitally for the geometric transformation and recitification of Landsat MSS images in digital form (Bernstein 1976). A GCP is a physical feature detectable in a scene whose location (x, y) and elevation (z) are known precisely. In the context of Landsat, typical GCP's are airport runway and highway intersections, distinctive woods or field patterns, prominent land/water features (e.g. small islands, river junctions and bends, distinctive promontaries, etc.). The area around each GCP is recorded as a 50 x 50 pixel or similar sized sub-image and stored in a library on the computer. When a new Landsat MSS image has to be processed a matching operation (template matching) takes place to precisely locate the same feature in the new scene, using computationally efficient routines. If a series of suitably positioned GCP's is located, geometrical corrections (rectification) can then be applied to the whole of the scene. This idea has been implemented on a production basis in the U.K. where a GCP library of 1,500 points (covering over 40 MSS scenes) has been created by the Royal Aircraft Establishment (RAE) Farnborough (Gordon 1981). This has been applied to the geometric correction of any new scene or repeat image, including its location on the U.K. national grid system (Benny 1981) and also for the construction of mosaics of several scenes using digital techniques (Mersen 1981). The development of this idea for the purposes of absolute orientation, aerial triangulation, etc. in photogrammetric work is an obvious extension of the technique, provided all-digital data is available.

b) Digital Measuring Systems

Turning next to the matter of the measuring equipment, it is apparent that completely digital and analytical solutions which cut out the need for an expensive comparator unit are also possible when digital image data is available. In this respect, it is possible to make use of and incorporate video technology which has been rapidly developed in recent years under the influence of the mass home video market but which has not as yet been exploited to any marked degree in photogrammetric instrumentation. Besides the mass storage offered by video cassette tape and video disks, a large variety of digitally-based video components exist which can be linked together to create photogrammetric measuring systems.

An example is the computer-assisted monocomparator assembled at the University of Glasgow (Figs. 17 to 21). This consists of the following components:

i) a video cassette recorder/playback unit which may use either the professional U-matic or the domestic VHS format;

ii) a frame memory which converts the analogue video images to digital form;

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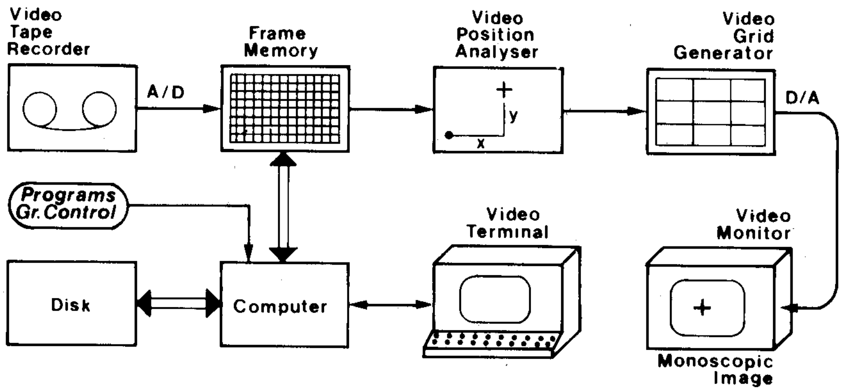

Fig.17 Video-based Mono-comparator connected on-line to Computer.

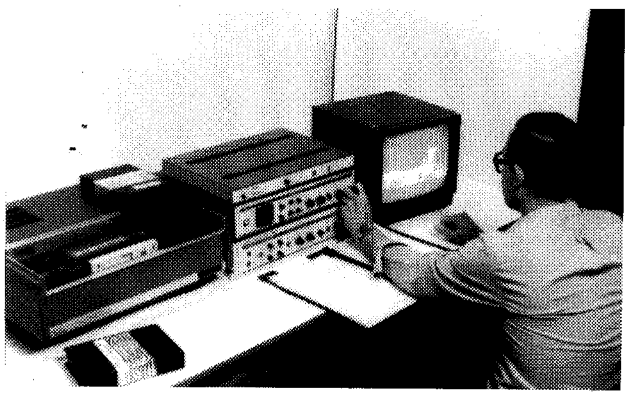

Fig.18 Video-based Monocomparator (Overall View).

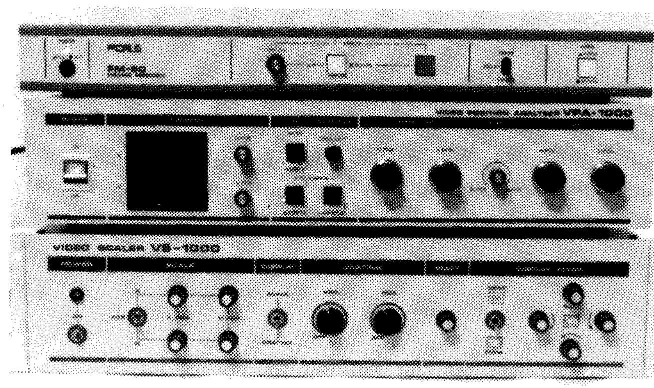

Fig.19 Frame Memory (Top) + Video Position Analyser (Middle) + Video Grid Generator (Bottom).

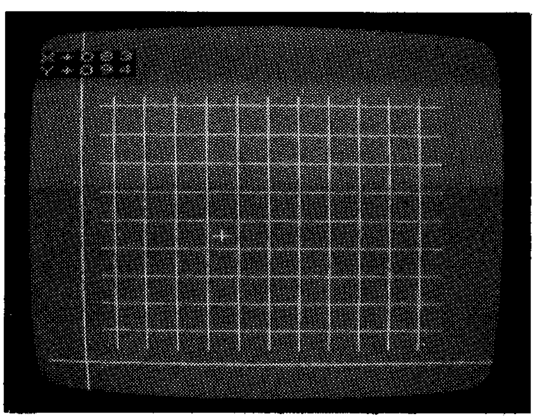

Fig.20 Electronically Generated Grid with crosshairs + x and y Pixel Coordinate Display.

Fig.21 Measurement on Video Monitor with crosshairs + x and y Pixel Coordinate Display.

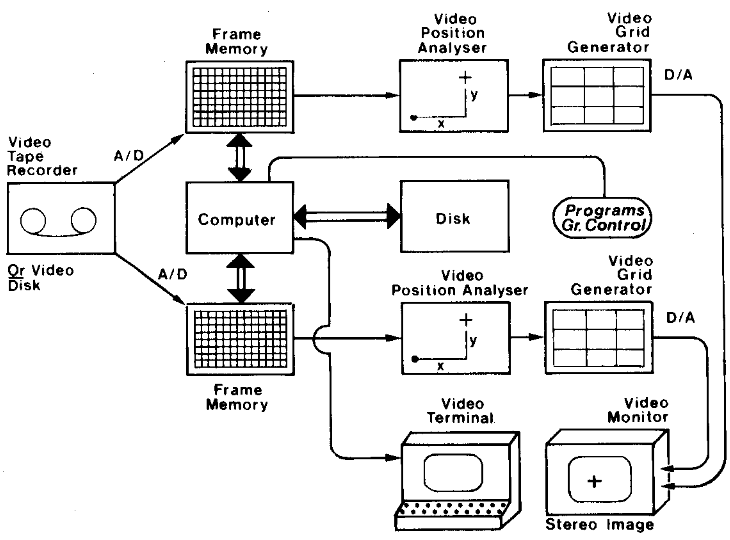

Fig.22 Video-based Stereocomparator connected on-line to Computer.

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iii) a video position analyser which permits the introduction of a measuring cursor or cross hairs and the direct measurement of its position in the image in terms of x and y coordinates expressed in pixel counts;

iv) a video scaler which allows the superimposition of a grid to check metric accuracy; and

v) a standard PAL (625 line, 50 Hz) monochrome video monitor.

Measurements on this system have been made using image data collected by the Barr and Stroud IR-18 infra-red camera mentioned above and recorded on a U-matic recorder. The accuracy of pointing using grid measurements is very high - to sub-pixel level. Both the digital image data itself and the measured x and y coordinates can be transferred to an on-line computer using standard interfaces. The cost of all this equipment (items (i) to (v) above) which has been assembled from off-the shelf items available from a professional video shop is under £ 5,000 !

It is immediately apparent that an all-digital video-based stereocomparator can be assembled using the same basic components (Fig. 22). This does immediately raise the question of carrying out stereoscopic (3-dimensional) viewing and measurement using video monitors. There are in fact a wide variety of possible methods, many of which are very similar to those used in existing analogue stereo-plotting machines. These include the following:

i) The use of a single screen on which the two component images appear side-by-side and are viewed by a hood containing two lenses with prismatic wedges which may be directed towards the two component images making up the stereo-model (Fig. 23). Essentially this is analogous to a lens stereoscope. A disadvantage of the arrangement is that it reduces the coverage to only half the size of the video monitor screen.

ii) This latter difficulty can of course be overcome by using two screens viewed simultaneously using a semi-reflecting mirror (Fig. 24). The required image separation is produced by insertion of horizontally and vertically polarised sheets in front of the two screens, the operator wearing spectacles with corresponding filters to produce the three-dimensional effect. This arrangement has in fact already been adopted by Matra in its Video Correlator Compiler (VCC) (Fig. 16).

iii) It is also possible to use a single screen with a semi-reflecting mirror and polarising filters for stereoscopic viewing (Ortony 1971). As shown in Figs. 28 to 30, this requires the two component images to be displayed simultaneously on the upper and lower halves of the screen (the upper image being inverted). Three-dimensional viewing is again achieved by the observers using polarizing filters. Like solution i), the ability of only half the screen is a disadvantage in term of either coverage or resolution.

iv) Another solution familiar to photogrammetrists from optical projection stereo-plotting machines is the use of complementary (red/green) anaglyphic images. Applied to stereo-television, this requires the use of a single colour video monitor, in which the red gun displays the left-hand image (for example) and the green, the right image. The operator views with the familiar anaglyphic filters (Fig. 25).

v) An alternative approach is that of the so-called "direction selective method" (Fig. 26). The two component images are displayed as alternating vertical strips of information (image data) on the video monitor tube. A lenticular screen consisting of an array of cylindrical lenses directs left and right hand images to the left and right eyes of the observer. Solid state screens are being developed which will allow two perfectly matched pictures to be produced. While this solution gets rid of the need for spectacles, it is rather restrictive in terms of the observer's position and the resolution is reduced in the horizontal direction. These difficulties may be removed by the use of two projection television tubes rear-projecting the two images on to a dual lenticular screen with a diffusing screen sandwiched between them (Fig. 27).

vi) Finally, another solution which is already known to photogrammetrists is to use alternating shutters (Roese and Khalafalla, 1976; Roese and McCleary, 1979). On the video monitor screen, the two component left and right hand images of the stereo-image are displayed at the television refresh rate (50 Hz). All the odd-numbered frames (1, 3, 5...) display the left-hand image and all the even numbered frames (2, 4, 6...) display the right-hand image. Viewing is achieved by using spectacles equipped with high-speed electronic shutters employing lead lanthanum zirconate titanate (PLZT) ferro-electric ceramics which can switch their state (open or closed) in one millisecond (Figs. 31 and 32).

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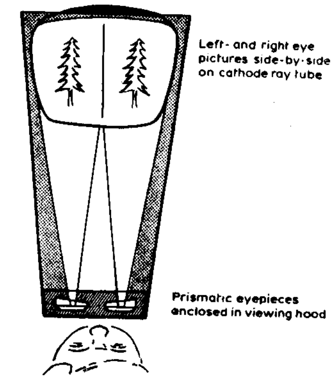

Fig.23 Split Screen with Lens Stereoscope.

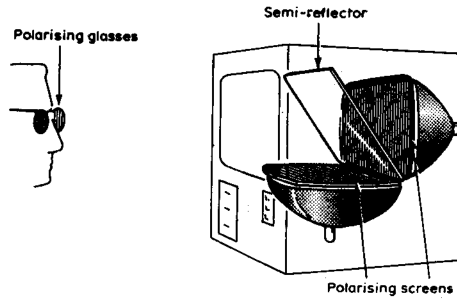

Fig.24 Dual Screens + Semi-Reflecting Mirror + Polarising Filters.

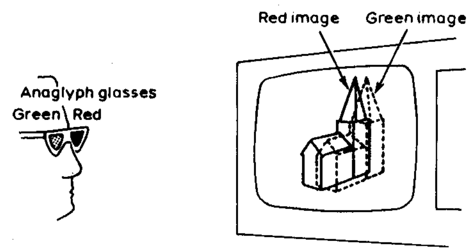

Fig.25 Use of Anaglyptics System with Single Screen (Colour Monitor).

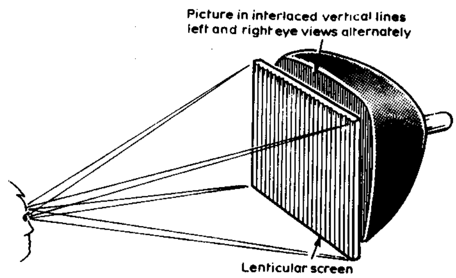

Fig.26 Single Screen with Lenticular Screen.

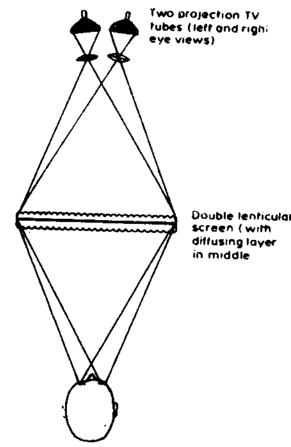

Fig.27 Two Televisions Rear Projecting on to Dual Lenticular Screens.

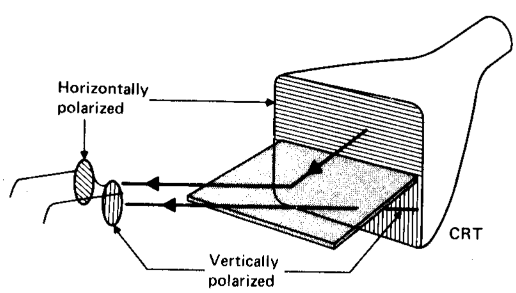

Fig.28 Single Split-Screen + Semi-Reflecting Mirror + Polarising Filters. (Perspective View).

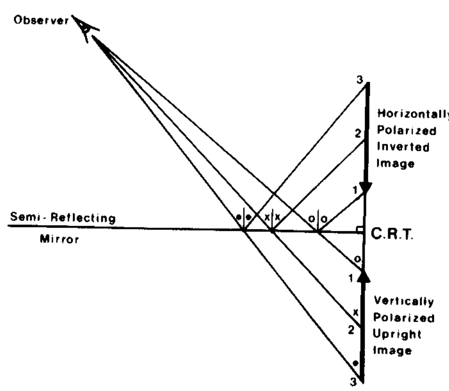

Fig.29 Single Split-Screen + Semi-Reflecting Mirror (Sectional Diagram)

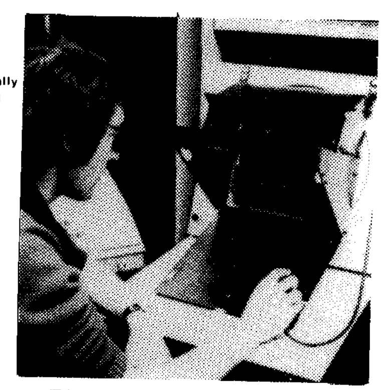

Fig.30 Single Split-Screen + Semi-Reflecting Mirror (Actual Example).

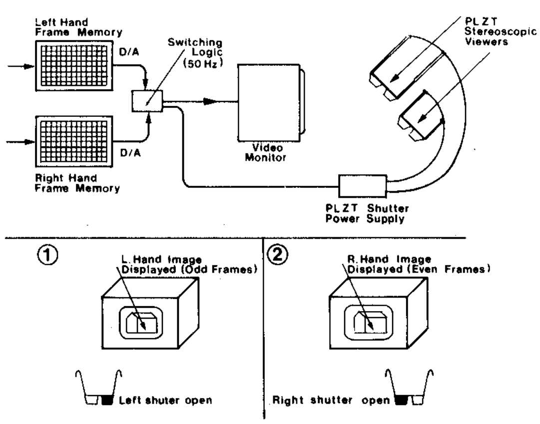

Fig.31 Use of PLZT Spectacles (Alternating Shutters).

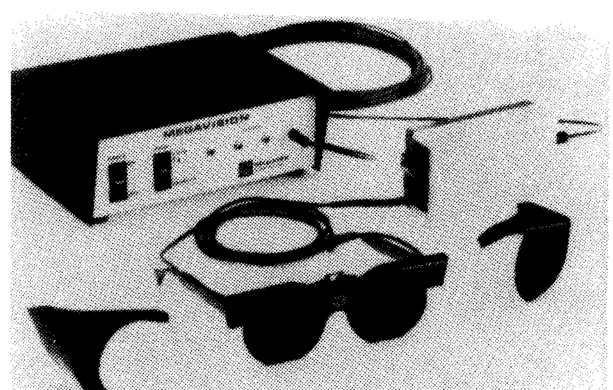

Fig.32 PLZT Control Unit and Spectacles (Megavision).

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It will be noticed that a particular merit of most of these systems is that they allow several observers to view the three-dimensional image simultaneously. The lack of expensive optical components and trains can only be an advantage also. What is clear too is that these various possibilities discussed above offer the photogrammetric systems designers of the future a wide choice of methods by which users may continue to employ stereoscopic viewing for both the measurement and interpretation of digital image data with all the advantages they presently enjoy from three-dimensional presentations.

Returning to the matter of the video/digital type of stereocomparator outlined above in Fig. 22, it is not too difficult to enlarge the concept to that of a full-blown all-digital analytical plotter. All the required components for such an instrument exist, though their integration and interfacing is a far from trivial task as is the digital image processing required to maintain the continuous orientation and formation of the stereo-model.

An inevitable consequence of the advent of the wholly digital and analytical approach to solving photogrammetric problems outlined in this paper would be the change in status of the organisations supplying photogrammetric equipment to the users. From being manufacturers of precision optical mechanical instruments, they would become suppliers of digitally-based systems. In this situation, most of the hardware components such as computers, video equipment, etc. would be bought off-the-shelf from the appropriate specialist suppliers. The interfacing and integration of these components into a photogrammetric system would be a primary task of the systems supplier, whose other principal concern would be the development, supply and maintenance of the relevant software to suit the needs of the individual user. Rapid developments along such lines have been apparent recently among the suppliers of computer-aided design (CAD) systems, the principal suppliers having largely dropped out of manufacture of hardware items such as digitizers, graphic displays and plotters to follow such a systems approach. A similar development can easily be envisaged with digital and analytical photogrammetric systems.

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Abstract

Digital and analytical photogrammetric systems and procedures are first defined and their various interrelationships are then explored. This introduction is followed by a discussion of the reasons for adopting such systems and the potential benefits of doing so. Next, a review is made of the extent to which digital and analytical systems have actually been implemented in the different parts of the photogrammetric process and the degree of success achieved in each part up till now. The special problems - technical, instrumental, organisational, personnel, etc - arising from and associated with the introduction of digital and analytical systems are discussed in some detail. Finally, for the future, the possibilities of a wholly digital and analytical system are outlined in which the use of a radically different technology and methodology is envisaged as compared with these in use at the present time.

ÜBER DIE KONZEPTION ANALYTISCHER UND DIGITALER SYSTEME

Zusammenfassung

Zunächst werden digitale und analytische photogrammetrische Systeme und Verfahren definiert und ihre verschiedenen Beziehungen aufgezeigt. Nach dieser Einleitung werden die Gründe für die Einführung derartiger Systeme und ihre möglichen Vorteile diskutiert. Es folgt eine Übersicht, inwieweit digitale und analytische Systeme tatsächlich in die verschiedenen Phasen des photogrammetrischen Prozesses integriert sind und wie erfolgreich sie sich jeweils bis heute bewährt haben. Die besonderen Probleme - technischer, instrumenteller, organisatorischer Art usw. - die mit den digitalen und analytischen Systemen verbunden sind, werden dabei im einzelnen diskutiert. Abschließend werden im Hinblick auf die zukünftige Entwicklung die Möglichkeiten eines völlig digitalen und analytischen Systems umrissen, dessen Technologie und Methodik sich radikal von den derzeitigen Systemen unterscheidet.

PHILOSOPHIE DES SYSTEMES ANALYTIQUES ET NUMERIQUES

Résumé

L'exposé définit les systèmes et les procédés photogrammétriques numériques et analytiques et analyse leurs relations mutuelles. Cette introduction est suivie d'une discussion sur le bien-fondé de tels systèmes et sur les bénéfices que l'on peut en tirer respectivement, puis d'une vue d'ensemble sur l'extension des systèmes numériques et analytiques dans les différentes phases du processus photogrammétrique et sur le succès constaté respectivement. Les problèmes spéciaux - techniques, instrumentaux, organisationnels, personnels etc. - liés aux systèmes numériques et analytiques sont discutés en détail. En conclusion, l'exposé souligne pour l'avenir les possibilités d'un système entièrement numérique et analytique pour lequel on envisage une technologie et une méthodologie tout à fait différentes des systèmes actuels.

LA FILOSOFIA DE LOS SISTEMAS ANALITICOS Y DIGITALES

Resumen

En primer lugar, se definen los sistemas y métodos fotogramétricos tanto digitales como analíticos y se explican las varias relaciones existentes entre los mismos. Después de esta introducción se exponen los motivos del empleo de los sistemas de esta índole y sus posibles ventajas. Sigue una sinopsis de la integración efectiva de sistemas digitales y analíticos en las distintas fases del proceso fotogramétrico así como del éxito que cada uno de ellos ha tenido hasta la fecha. Se exponen con todos sus detalles los problemas específicos de tipo técnico, instrumental y organizatorio, etc., relacionados con los sistemas analíticos y digitales. Finalmente y con vista al desarrollo en el futuro, se esbozan las posibilidades que brindará un sistema totalmente digital y analítico, cuyas tecnología y metodología difieren fundamentalmente de los sistemas utilizados en la actualidad.

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