*Photogrammetria*, 40 (1986) 257—298
Elsevier Science Publishers B.V., Amsterdam — Printed in The Netherlands


# OPERATIONAL ASPECTS OF ON-LINE PHOTOTRIANGULATION

EGON DORRER
*Munich Bundeswehr University, 8014 Neubiberg, FR Germany*
(Accepted for publication February 10, 1986)

ABSTRACT

Dorrer, E., 1986. Operational aspects of on-line phototriangulation. *Photogrammetria*, 40: 257—298.

The basic objectives of on-line phototriangulation (OLT), viz. reduction of preparatory work, acceleration and facilitation of data collection, effective quality control of the data, can only be met if, both adequately designed user-friendly operating procedures and theoretically sound functional solutions are provided by the manufacturers. This is presently by far not the case. The article attempts to show how the on-line approach significantly simplifies the organization of the work as compared to conventional off-line methods. The necessity of effective man/machine interfaces is particularly stressed, as the human being must be considered a primary system component. Well-designed operating procedures must provide a maximum of guidance and only a minimum of necessary flexibility and freedom to the operator. Also, OLT should entirely be based on bundles rather than on independent models.

## 1 INTRODUCTION

Phototriangulation is a method of photogrammetrically establishing supplementary ground control through the geometric relationship of overlapping photographs forming strips or blocks. Within the entire chain of photogrammetric tasks, however, triangulation is only one, though rather significant component. Manifested by a thorough theoretical background, its worldwide use for surveying applications to a multitude of projects has proven its validity in photogrammetric practice. As they have emerged through time, the basically four phases of phototriangulation, viz. preparation, mensuration, quality control, and adjustment, are solved with the help of special hardware equipment, such as point-marking devices, mono- or stereocomparators, precision stereoplotters, recording devices, digital computers, and with sophisticated software developments. Called "off-line triangulation", this process is, however, time-consuming, highly susceptible to different kinds of errors and blunders, difficult for monitoring its clearly separated phases, demanding in terms of skilled personnel, and costly.

Revised version of a paper having been presented at the ISPRS-Congress Rio de Janeiro 1984.

0031-8663/86/$03.50 

With the recent expansion of computer-assisted and controlled on-line photogrammetric systems, and the generally increasing desire to utilize this dedicated computing power for phototriangulation and block adjustment, caused by growing demands for both quality and quantity of supplementary control surveys, the idea of a particular "on-line triangulation" has become attractive and operationally feasible. The basic objectives of On-Line Phototriangulation (OLT) are:
— to reduce the preparatory work in terms of time and cost;
— to accelerate and facilitate the process of data acquisition;
— to control the quality of the collected data; and
— to either properly prepare the triangulation data for suitable off-line adjustment or perform an on-line adjustment.

Although OLT-methods may be applied in conjunction with computer-supported comparators or analog stereoplotters (see e.g. Höhle et al., 1982; Methley et al., 1982; Ellenbeck, 1983a; Schreiber, 1983), it is justly assumed that real advantages can only be expected with analytical stereo restitution systems. This is the reason why Working Group III-2 has restricted its actual topic to pure analytical systems (Kratky, 1982b).

The photogrammetrist expects from OLT a substantial increase in the overall cost effectiveness of phototriangulation work. According to Brindöpke (1983), presently at least 50% of the total triangulation time must be attributed to preparatory work, e.g. point transfer. On average, he also expects one blunder or gross error to occur in every fourth model or picture. This in turn necessitates a series of computer runs during the block adjustment phase, otherwise equally expensive computer runs of sophisticated data-snooping programs are needed (Klein and Förstner, 1981). Brindöpke's data reveal also that, from a total of 5000 routinely triangulated photographs in 1982, analytical stereoplotter and comparator measurements yield the same accuracy after bundle block adjustment. By virtue of this result, any objections to the use of analytical systems for phototriangulation in a production environment, would therefore be unfounded. The photogrammetric end user thus has a legitimate interest that highly efficient on-line methods be available for analytical triangulation systems (Ellenbeck, 1983a, b).

Unfortunately, the majority of analytical systems manufacturers provide neither adequately designed user-friendly operating procedures, nor theoretically sound or suitable functional solutions for the triangulation process. Today, many photogrammetrists using analytical stereoplotters as triangulation instruments are increasingly becoming aware of the various design deficiencies of these computer-based systems. This mainly concerns operating aspects with which the human operator is directly confronted. The reason seems to stem from the fact that photogrammetric instrument manufacturers, by tradition, always have had to direct their attention to precise mechanical and optical hardware design. However, analytical photogrammetric instruments, which are entirely dependent on computer support and control, have gained a much higher degree of intelligence, and are, at least in principle, capable of undertaking many tasks previously considered as typically human. And it is these software-governed procedures with which the manufacturers now have to deal, without having sufficient experience as well as comprehension nor real appreciation of the needs and problems of the end user. Seymour and Derouchie (1978) state, not without good reason, that the biggest lesson they have learned is that purely computational software is trivial when compared to the software required for good operator communication, data manipulation, and operational flow control.

In a series of articles Kratky (1978, 1980a, b, 1982a, c) has outlined and discussed the general principles of OLT, based partly on the philosophy of the National Research Council of Canada and partly on a comprehensive and scientifically objective methodology. One of his most significant conclusions is that, while there are still several theoretical and formal problems to be solved, the process of OLT primarily is governed by operational aspects. The reason is that OLT on an analytical instrument consists of a series of interlocked procedures involving continuous interactions with the human operator. Kratky (1981) discusses particularly the operational advantages of an optimally designed OLT. The on-line capability to combine mensuration and data processing increases the speed and the reliability of all operations, changes some of the traditional techniques, and has an impact on the overall organization. Operational aspects of OLT to a varying degree are also described by Vigneron and Dubuisson (1979) for the Traster, Turner (1982) for the ANAPLOT-III, Seymour and Derouchie (1978) for the US-1, Hobbie (1979) for the Planicomp, Carl Zeiss (1980) for the Planicomp, US-2 (1983) for the US-2, and Kern (1983) for the DSR-1. In his doctoral thesis, Liao (1982) makes several profound investigations into automatic point transfer by discussing particular operational problems for the AP/C-3.

It is a well-known fact that the majority of errors in the data will arise at the observational stage of data acquisition and during any other human interaction. Therefore, facilities for verifying the data immediately after observation or entry have much merit (Methley et al., 1982). Essential are automatic conditional checks according to the geometric configuration of the gradually built-up block compound. This on-line quality control has recently gained considerable interest partly from a theoretical point of view (Amer, 1981; Molenaar, 1981, 1983; Grün, 1981, 1982a, b; Klein and Förstner, 1981; Kilpelä et al., 1982; Radwan et al., 1982) and partly from the more operational aspect (El-Hakim, 1982, 1983; El-Hakim and Kratky, 1982; El-Hakim and Ziemann, 1982; Masson d'Autumne and Giraudin, 1982; Kratky and El-Hakim, 1983). However, computer-assisted error detection and localization without the possibility of human interference through suitable editing features cannot provide highest efficiency. In addition, one of the main advantages of OLT is to directly suppress errors of coming into being at all by properly organized mensuration schemes in conjunction with — whenever possible — computer-supported point identification and positioning (Ellenbeck, 1983b). These characteristics have been particularly stressed by Dorrer

(1981), Kratky (1981) and Liao (1982). The latter two and Grün (1982a, b, 1983) arrive at the significant conclusion that the physical transfer of triangulation tie points can be made fully obsolete, and that of pass points for subsequent stereo compilation at least partially.

Although the ultimate goal of OLT is on-line block adjustment (Molenaar, 1983), it seems that sufficiently fast numerical solutions cannot be realized at the present state of technology (Dowideit, 1980, 1982). This holds for the application of both direct and sequential methods. Appearing rather attractive to OLT, sequential or recursive solutions additionally suffer from the unsurmountable fact that due to the nonlinear functional model systematic deviations of the estimated quantities are inevitable with the increasing number of photographs. Blais (1982) and Grün (1982c) describe different recursive optimal algorithms applicable to small strips. For practical applications presently only off-line block adjustment is feasible. It is therefore mandatory that OLT prepare and store its results for off-line processing in a portable and efficiently structured data base. All instrument manufacturers refer to this important fact, but it is doubtful if the conditions required for general portability and compatibility are met. Steidler (1983) reports of a systematically designed software package for one particular system.

## 2 NECESSITY OF EFFECTIVE MAN/MACHINE INTERFACES

The primary goal of OLT is to achieve a high degree of reliability of the measured data. As the human operator must be considered as a primary system component within the triangulation process, he plays the key role by maintaining full control over it, functioning both as an editor of the data and coordinator of procedures (Kratky, 1981). In a profound study, Kröll (1981) has emphasized this phenomenon for the first time from a modern system engineering point of view. When looking into existing analytical stereo restitution systems, however, one cannot help stating that in many cases the instrument manufacturers never really have adequately considered this important fact until perhaps the very last minute. Petrie (1983) is therefore rather sceptical of the claims issued by all manufacturers of computer-based photogrammetric systems which emphasize their user-friendliness. He clearly states that "....we are still far from providing systems which are efficient and comfortable from the operational point of view". By investigating the essential working phases of OLT, Dorrer and Kröll (1982) have critically pointed out the indispensable necessity of incorporating modern ergonometric principles into analytical system design.

The effectiveness of a computer-based system is limited by the efficiency of the interface through which it is utilized and controlled by people. It is therefore important to incorporate human capabilities and limitations as explicit elements in the total system design, develop systems that reduce and compensate for human error, apply ergonomics to equipment and workspace design, develop man/machine dialogues that optimize communication, and improve system and operator productivity by designing user-friendly hardware and software. In an ergonomically well-designed system the human operator feels comfortable all the time, is enabled to visually pursue and monitor machine actions on properly placed interactive devices, has all needed information right at his fingertips, never has to wait longer than absolutely necessary, and always will be instructed rather than punished for incorrect or inadmissable operations. In other words, the system transmits a feeling of trust.

### *2.1 Ergonomics*

The objective of ergonomics in general is to find a suitable symbiosis of technical innovation with the humanization of work. By a rational view of human functions in interplay with his work, ergonomics aims at optimal adjustments of this work and the working environment to the nature, limitations, and possibilities of the human being. In this context, work is considered as any purposive human action as well as all physiological activities. The history of technical evolution has almost exclusively shown the reverse tendency, viz. the enforced adaptation of the human being to often inhumane or physically and psychically harmful working conditions dictated by machines. Forced by modern technology and by increasing pressures for optimized efficiency, the manufacturers of computer-based systems realize more and more that, by properly designing the human element into a system right from the start, hardware and software investments will be rewarded by optimal performance of the final product. The benefits of human factors engineering are increased productivity and performance, minimized stress and human error, reduced skill-level requirements. Today, computer-based systems must subordinate to the requirements of the human operator (Eggenberger, 1983).

The most significant activities of the human operator within an OLT-system are the precise and reliable measurement of singular points by meticulously observing stereo photographs, and the principal organization of complex procedures by making high-level decisions. These responsible and essential tasks must be properly supported by the computer through software and facilitated by compliance with basic anthropometric conditions (Dorrer and Kröll, 1982) through hardware. While the software governs the main data and information flow of the triangulation process, the available hardware interacts directly with the human being, i.e. his visual system and his tactile and auditory senses. Anthropometric conditions are met if the various elements of the workspace are well within reach of the associated human senses. Although none of these questions concern OLT alone, a bad hardware design can make the life of the phototriangulation operator miserable and his performance inefficient.

If, for instance, frequently needed primary switches or keys are placed directly beside less important ones, the operator always has to look in their direction when having to activate them, at the same time losing sight of the stereomodel. Similarly, the general keyboard may be placed aside from the operator's seat and too far from the control panel, thus compelling the operator to always turn around. Some systems do not provide a simple way or no way at all for monitoring the current position of the floating mark within the picture format. Quick changes between low/high speeds of the input controls cannot be attained in some systems, because they require special routine calls. In almost all analytical systems, the CRT display is too far apart from the stereo viewer, and only one manufacturer eliminated the otherwise tiresome necessity for visual far/near accommodation by using a stereo monitor to be watched through special glasses. Although experience with a few analytical systems shows that a special parallax footswitch is probably the most optimal device for efficient phototriangulation measurements, other systems rather prefer hand controls.

Graphic digitizers or tablets using a "mouse" for cursor control as an ergonomically excellent alternative to the $X$-$Y$-handwheels are offered only by two manufacturers. These input devices may be advantageously used during the preparatory phase, as has been shown by Ellenbeck (1983a). As could be demonstrated by a few systems, a heavy and high-torque tracking ball can be adequately substituted for the traditional handwheels, although many operators would not want to miss them. Only one manufacturer has made an effort in providing a well-functioning solution to the very significant operational task of optionally averaging successive measurements. All other systems constrain the operator to predetermined either single or double measurements. Although it seems logical and natural that auditory displays are extensively used by a system, e.g. to properly acknowledge a measurement or recording and thus relieving the operator from having to turn his head to some visual display, this may not always be the case. All presently available systems require the operator to enter properly specified point-identification numbers, mostly even restricted to certain limited ranges according to the type of the point or due to inherent memory restrictions. Such confinements are highly prone to human error and should be avoided by all means, e.g. by automatic numbering and/or utilization of automatic voice-recognition processors. Dorrer and Kröll (1982) propagate the use of a graphics terminal for monitoring the actual state of progress during OLT.

There is still considerable dispute as to whether the human operator needs both a CRT with general key board and a separate control panel. A CRT provides a method of communication for such purposes as tutorials, instructions and on-line editing. Yet the operator most often only wants to routinely tell the machine what to do in the most direct way. Hence, a control board or panel has significant advantages. Generally, however, a vast majority of operator commands and data input and output is now performed through the CRT. It significantly increases the flexibility of the system by its conversational interactive mode. It also eliminates part of the traditional interface, as the CRT uses standardized interfaces, e.g. RS-232. Thus, the costs of the system will be reduced. From the ergonomic point of view a suitable compromise will yield optimal solutions. The inevitable keyboard should be positioned directly in front of the operator, with the CRT just above the keyboard and below the eye pieces. Since the tactile senses of the human are mainly concentrated on the handwheels, a somewhat reduced control panel should be subdivided into two parts, each placed in close contact to either handwheel. This arrangement guarantees fast yet reliable control facilities, e.g. low/high speed switch, interrupt switch, single/multiple measurement switch, previous machine action "undo"-switch, recall switch, etc. At least one foot switch should be designed as general mode switch, e.g. for changing from coordinate to parallax mode. These features are so important for a user-friendly and efficient operation that they cannot be overemphasized.

For close-range phototriangulation or for projects involving different kinds of imagery, quick differential zooming and adaptations of the floating mark to varying magnifications and densities are becoming increasingly important. Not all manufacturers of analytical systems, however, have realized this. Ultimately, all these essential features should be software-controlled, although high cost may motivate a manufacturer to adhere to pure hardware design. Controls responsible for switching between Ortho/Pseudo or Positive/Negative should be software-governed by all means. In general, the flexibility of an OLT-system can be considerable enhanced if all switches, keys, and other input controls are governed by software rather than hardware. If, by chance, something would happen to the control system, e.g. blocking of handwheels, the operator could thus directly be notified on the CRT. Otherwise, forgetting to turn a hardware toggle switch at the right time will definitely cause a nonrecoverable program failure and unnecessary punishment of the operator.

In summary, from a theoretical point of view, always four kinds of controls should be considered in a good and ergonomic OLT solution, viz.:

(a) Action for the activation of certain functions, operations or commands by means of keys or a menu.
(b) Flags for switching between two or three different low-level functional states by means of switches.
(c) Modes for changing from one high level functional state to another e.g. orientation mode, recording mode, controlled by means of switches.
(d) Measurement, i.e. a state always in a real-time loop that can only be interrupted by an action. Control wheels.

### *2.2 Operating procedures*

Although essentially all analytical stereoplotter systems have the same kind of hardware components, they may considerably differ from each other by architectural characteristics. The key component of analytical systems, however, is software, as it makes the instrument perform, viz. by functionally and more or less ingeniously tying together the various hardware components with the human interfaces. Performance differences caused by software can therefore be expected to be even much more pronounced. The human operator communicates with the computer-based instrument through operating procedures. This special class of application programs provides an interface to the user and represents the framework of the entire software structure. Helava (1982) justly states that a well-designed set of operating procedures:

— makes the instrument efficient and easy to use;
— gives the operator all support and flexibility he needs;
— does not load the operator with unnecessary tasks;
— is adaptable to various situations, operator skill levels, and procedures;
— ties together the programs in various levels.

Operating procedures thus can make more difference in the performance of analytical systems than any other part of software.

An analysis of bridging operating procedures for OLT in existing analytical stereoplotters reveals a spectrum ranging from almost the worst design conceivable to virtually ideal solutions. This rather discouraging finding is probably due to the traditional way of off-line programming. Many efforts have been put into adapting the phototriangulation output data to existing off-line block adjustment programs. However, attention has not been focused to the real necessity of a "user-friendly" software for the on-line data gathering task. It seems very often as if the software designer tacitly assumed his program to be the only possible solution. Yet, experience shows that most of the, by nature, highly interactive software has obviously been created during an epoch when "user-friendliness", "optimal man/machine interaction", and "ergonomics" were not considered important. Many such programs have been designed in a pure off-line or batch mode mentality for which the human — if at all — exists only marginally.

Many of the design deficiencies are not so much severe from the point of view of an operator who is continuously working with the system. The beginner or occasional triangulation user of an analytical plotter, however, may have to find his way through operating manuals — issued by the instrument manufacturer — written in an often too concise, sometimes even contradictory or misleading and unexpected, hence obscure way. Frequently, the manuals assume that the user has already attended a special instruction course. The user ought to be allowed to expect from the manufacturer a well-written manual which explains in detail the handling of the various procedures and routines, unambiguously discusses the necessary alternatives, illustrated by realistic examples. Checklists or quick reference guides alone are good only for the continuous user. Systems that rigorously employ menu techniques can have especially valuable HELP-facilities and are therefore superior to other systems. Operating manuals frequently refer to "...that this or that should not or must not be done during a certain situation, in order to avoid certain undesired or unrecoverable program failures...". In well-designed operating procedures such verbal warnings are either displayed on the screen as preventive warning messages, or they are not required at all, for all potential hazardous input devices have been temporarily locked.

In some existing systems, the locking of a particular photo stage during bridging must be initiated manually with a special (hardware) switch. If done inadvertantly, the handwheels may become inactive in one such system, thus interrupting pursuance of further measurements. In another system, erroneous parallaxes are introduced if actual and anticipated point type do not correspond. Almost all systems expect the operator to repeatedly check or activate several switches for otherwise simple operations. This especially concerns toggle switches for distinguishing between BASE IN/OUT, ORTHO-/PSEUDOscopic, LEFT/RIGHT PHOTO FIXED, BRIDGING YES/NO. Whether these switches are hardware- or software-controlled is irrelevant, since in essence, the required operating procedures for bridging were poorly designed anyhow. None of these switches (except perhaps BASE IN/OUT) would be needed at all in a real good bridging software design, because all their functions are directly dependent on the choice of the base in/out switch. The bridging yes/no switch is completely obsolete in a specially programmed bridging mode.

Another potential source of deficiencies in operating procedures lies in the manipulation of different types of points during bridging. There are many solutions conceivable for simultaneously handling old or new tie points, old or new control points, orientation points, auxiliary points, pass points. It all depends whether point id-numbers have to be entered manually or if they are automatically generated, whether or not the system automatically pursues a preselected pattern and sequence of points partially or entirely, whether or not the operator temporarily can escape from the point pattern and change point types or select others, how consecutive photographs are connected, etc., etc. In the bridging procedure of one particular stereoplotter the operator is expected to constantly make decisions and to think about his next moves as to what type of point is to be measured, what sign the id-number should be given, when points are to be "skipped", whether to position points manually or not, if the various toggle switches are properly turned, where to store the measured point data and to check if the point memory already is full, whether the parallax foot switch has to be engaged for measurement or not. Obviously, operators of such an instrument can only be considered experienced after a rather lengthy and combersome learning period. A special checklist is indispensable in this particular system, because without it, the operator would quickly and easily forget the right sequence of operations. But even a checklist does not guarantee freedom of severe blunders. Strictly speaking, the analytical system expects too much from the human operator.

These few examples demonstrate that operating procedures providing a maximum of flexibility and freedom to the human operator are poorly designed. On the contrary, well-designed operating systems must provide a maximum of guidance and only a minimum of necessary flexibility or freedom. The human operator has to be relieved of any unnecessary, repetitive, non-obvious, illogical, easy-to-forget, or alerting actions in the course of a measuring process demanding his continuous mental concentration. One essential objective of the human being within the system is precise and reliable point measurement, a task that must be properly supported by the computer. Any deviation from this self-evident principle causes uneasiness and reduces his confidence to the system. A good OLT-system does not put the burden on the operator's shoulders but rather relieves him from uncontrolled uneasiness, stress or psychological insecurity of the operations.

In a good operating environment, the operator should always be allowed to override any computer controls if he so desires. This entails the design of easily accessable facilities for interrupting running programs. Practically all existing analytical systems provide some kind of break functions for this important task in one way or another, though under different assumptions and with different objectives in mind. One particular manufacturer explicitly advocates the advantage of break functions for interrupting the current, normal mode for some time, and, after completion returning to the place at which the interrupt had occurred. This feature permits the checking or changing of the values of data items, the controlling of the CRT-display, and the identification of data items to be affected by the incremental input controls.

A crucial question is what to do when counting failures of the encoders occur. An efficient operational safety feature is to measure a reference point prior to finally exiting from the current stereomodel. The same readings as in the beginning would psychologically help the operator and give a clear "go ahead". Thus, safeguards are extremely important for smooth and reliable operations. Differences in the readings would indicate hardware failures that have to be meticulously traced back. One of the existing systems has particularly taken into account the possibility of restarting in the middle of a strip in the case of a program crash or power failure.

All operations associated with real-time or near real-time control may not unduely delay computer responses beyond intervals of time that are considered not fast by the human. The threshold lies between 1 and 3 seconds of time, anything longer is felt to be a waiting or pausing time. As an example, the combined relative/absolute orientation offered by one manufacturer always uses one routine for solving all twelve unknown orientation parameters. Although six of them are fixed in bridging, the routine nevertheless uses twelve, thus requiring a rather long time for the numerical solution, viz. some seven seconds on an 11/34. Because of this ergonomic failure, repeated program runs after some edited measurements would accumulate to exceptionally long waiting times. As other analytical bridging systems have demonstrated, a properly designed orientation routine never takes more than one second.

For practice, operational aspects are so important that the man/machine interface should be as simple as possible for the operator. In the course of any procedure he should not have more to think or reason than absolutely necessary for the current task. One of the most significant aids is the prepositioning feature of analytical systems, enabling fast and — when programmed properly — reliable and simple measurements. The operator does not even have to know where the floating mark is in the pictures or what type of point he is supposed to measure. One manufacturer offers an interactive relative orientation routine in which an artificial $y$-parallax of some 100 microns is introduced from the sixth orientation point on. This solution is user-friendly, as the operator at once implies that he now has to remove the $y$-parallax.

Many triangulation users of analytical systems have tried to partially bypass the revealed deficiencies by reprogramming some of the delivered software either by improving existing routines or writing own routines and incorporating these in the software system. Generally, this is a tedious task and may become critical or even hazardous if the original programs were not designed according to the principles of structured or modular programming. It may not be possible at all in case the manufacturer does not disclose the source software. Experience shows that alterations to the original programs must be considered as the normal rather than the exceptional, since many tasks and problems inherent to a particular user never can be anticipated by the software designer. The user-friendliness of any analytical system can also be rated according to how easy or difficult it is for the user to modify the existing OLT-software. Despite the fact that control computer systems and external memories are rapidly becoming more powerful and cheaper, software is and will remain the bottleneck for some time to come. We cannot overemphasize enough the statement that the user must gain access to the source code by all means, and that a manufacturer hiding his software actually is working against himself.

Most of the problems associated with modifications of real-time software are caused by insufficiently structured and poorly documented programs, and also by still missing standards for efficient man/computer dialogue. Structurization means that a program be segmented into a set of individual program modules. Particularly in real-time programs, however, segmentation ensues mostly from technical or administrative criteria, e.g. memory requirements or number of available programmers, rather than from functional aspects (Eggenberger, 1983). This results in unfavorably close interlocking of the modules, thus making the exchange of existing modules for new ones virtually impossible.

According to a modern approach to ergonomic software, the design of a user-friendly man/computer dialogue must follow the way people communicate with eachother, i.e. with words and syntax of the chosen language, and with nonverbal signals. The procedures and strategies which human operators have adopted for this communication are based on predictability, implication, experimentation, and motivation (Jones, 1978). The user does not treat everything new that he encounters for the first time, he expects to have at least some familiar aspects, his attitude is predictive as opposed to passive. Current computer dialogues take practically no account of this fact at all. For prediction to be made successfully, context or implied information must be provided, e.g. different sets of commands, reasonable default values.

People interact with the world around them experimentally, they do not passively accept once and for all a program of correct patterns of activity and from then onwards never make a mistake. Yet, usually the designers of man/computer dialogues assume that by issuing a manual the user will things get right the first time. Particularly in on-line systems "trial and error" can be one of the most significant and efficient features. Prerequisites for "trial and error", however, are that the penalty of making an error is not excessive, that the cost in terms of time, money and labour of making a trial must be low enough to allow several trials to be made, and that the outcome of the trial is available in sufficient detail to indicate what alterations to make for the next trial. A good interactive system will build up confidence as the user discovers that he will always be warned properly, and that he will be provided with adequate diagnostic and confirmatory messages. In order to be able to learn by mistake, diagnostic messages must be a form of computer-aided instruction.

Finally, a computer dialogue should deliberately try to generate the right feelings in the user instead of leaving the matter to chance. Not understanding the mysterious machine, the user, therefore, needs to feel his commands will be obeyed, that his data is in safe hands, and that the machine is informative and helpful.

The relative importance of the messages, distinguished between interrogations, statements and commands, can and should be consistently exploited by means of nonverbal signals in order to widen the rather limited "bandwidth" of current computer terminals. Issuing an auditory message to signalize, e.g., the acknowledgement of a measurement or a warning, reversing and flashing the video, or generating a pleasing layout of the display, are no luxuries at all. It is always annoying, e.g., that messages and prompts referring to actions or measurements which in the meantime have been discarded are still on display, thus making the layout difficult to read and concealing significant information.

It seems natural that a given application software system is based on menus and submenus, as these represent an immensely important communication facility. However, only the most recently offered analytical stereoplotters have it. A system without menu structure is not designed optimally according to human engineering principles, because ultimately only a real computer-controlled dialogue can guide and assist the user. User-controlled dialogue in complex real-time systems entails overloading and overtaxing the operator.

What would definitely be important is some kind of photogrammetric query system. Although it seems that only one of the existing analytical instruments has one, it could principally be provided for the others, too. Analogous to modern diagnostic programs, a special HELP command can explain in general what are its features, how it is to use, what specifyers are available, etc. HELP with a specifyer can then give specific and detailed information on what to do, etc.

## 3 FUNCTIONAL CONCEPTS

The methodology of analytical formulations for OLT generally is a subject in its own, and cannot be considered in this context. However, different functional approaches have a certain direct impact on selection, design and efficiency of the operating procedures. This mainly concerns the way of connecting successive stereopairs in a strip, the question whether an on-line strip or block adjustment is to be taken into account or not, the type of real-time input control routines, and the kind of transformations or corrections for the refinement of image and object coordinates.

### *3.1 Quest for suitable analytical bridging formulations*

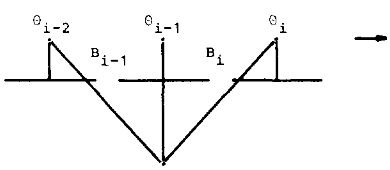
The basic mensuration and data processing unit for an analytical stereoplotter is given by a pair of homologous photographs forming a stereomodel by means of a spatial intersection of the associated bundles of rays. The realization of a stereomodel is fundamentally important for all such tasks where compilation of topographic or other features is the main objective. For phototriangulation, however, the stereomodel is of a temporary nature in order to facilitate the identification and interpretation of triangulation points, and to enable some quality control. The model coordinates which are derived from stereo-image coordinates should thus not be of primary concern to OLT. Contrary to the majority of analog stereoplotters allowing only independent model triangulation, the analytical stereoplotter conceptually has no limitations as, e.g. to the magnitude and direction of the base. It is, therefore, not only possible but also highly advisable to connect successive photographs, i.e. bundles, rather than models. Rigorous application of the base-in/out feature — as in the antique type of universal analog stereoplotter — allows the photograph common to two successive models to remain on its stage, an important property that not only immediately affects the practical aspects of operation, but also can be advantageously utilized for precision computer-controlled point positioning. This is described in detail in the next chapter.

Actually, there is no such thing as independent models in bridging, if the capability to switch between base-in and base-out is employed. Independent models have been devised as a logical consequence of combining the advantages of analog precision stereoplotters (base-in only) with the relative ease of developing off-line model block adjustment programs. Both these features emerged approximately at the same time some 20 years ago. In retrospective we may safely state today that independent model triangulation has to be considered an expedient only due to the then available means.

Model coordinates are derived and thus correlated quantities. In the context of an early, i.e. dynamic quality control during data collection, independent models are therefore less suitable indications of blunders than bundles. As limited computing power has become insignificant as compared to other problems, a well-designed OLT-program must be based on the principles of individual bundles through measured image coordinates. Only bundle methods take full advantage of the analytical stereoplotter. The manufacturers of analytical photogrammetric systems offering on-line independent model connection for bridging should be aware of the limitations and deficiencies of their method. The processing of stereomodels means that not only accuracy is given away, but also the power of detecting gross errors is not exploited to its fullest extent. This need not affect, though, the possibility of later off-line model or bundle adjustment.

Bridging logically refers to the forming of strips as larger computational units. At the present state of technology, a distinction is needed between two approaches of OLT, viz. either on-line triangulation with off-line adjustment, or both on-line triangulation and on-line adjustment. Due to the steadily increasing number of collected data, rigorous on-line adjustment of strips, let alone entire blocks, cannot be performed in near real-time. This would not be critical at all for purely photogrammetric measurements, because firstly the probability of making any measurement error is infinitesimally small in a well-designed OLT-system anyhow, and secondly additional powerful checks during the process of connecting successive photographs would immediately reveal any error. However, ground control coordinate errors can only be detected if a sufficiently large number of control points were already measured in the pictures, a situation which yields ever longer substrips. Only very few of the existing analytical systems make provision for at least some sort of on-line strip adjustment by polynomials in an interactive mode, i.e. by operator choice. Since both the interpolation by polynomials theoretically is unsound, and user-guided interactivity here ergonomically infavorable, this approach should only be considered as preliminary. The ultimate goal of OLT should be a genuine and indistinguishable combination of formation and adjustment of strips by means of sequential, hence on-line, connection of successive photographs and of accumulated substrips to ground control (Molenaar, 1983).

If analytical bridging were carried out the same way as in the early days of analog aerial triangulation with universal stereoplotters, e.g. the Planigraph C8, viz. first relative orientation of the new (dependent) photograph with respect to the old (independent) fixed photograph, followed by a simple scale transfer through height measurements, then this would result in a functionally as well as stochastically inferior solution. In that case, connecting independent models by spatial similarity transformations would be superior due to a higher degree of interdependence of the two adjacent models. Nevertheless, this antiquated bridging formulation is propagated in at least one of the existing analytical systems (Hobbie, 1979). Radwan et al. (1982) state not without good reasons that this type of bridging is expected to be the least accurate as scale and orientation are not determined simultaneously. Both higher precision and reliability can be attained with a combined determination of scale and rotation for the current stereomodel. Kratky (1980a), El-Hakim and Kratky (1982) and Kratky and El-Hakim (1983) describe in detail the mathematical model based on the coplanarity condition applied to all observed points and a modified collinearity condition applied only to tie points. They can clearly verify for the NRC analytical system that this simultaneous determination is superior to the two-phased solution. Similar favorable conclusions derived from a so-called scale-constrained relative orientation are reported by Kilpelä et al. (1982). Radwan et al. (1982) arrive at analogous results by utilizing triplets and quadruplets as basic computational units. A significant byproduct of some of these investigations is that, as Radwan et al. (1982) and Kratky (1980b) have explicitly stated, any further increase in size of the basic computational unit beyond triplets does not seem to be of any advantage unless a sufficient number of control points is available. Masson d'Autumne and Giraudin




RELATIVE ORIENTATION AND SCALE TRANSFER:

$$r(\underline{\Theta_{i-1}}, B_i, \Theta_i) = 0$$
$$s(B_i) = 0$$

SCALE RESTRAINED RELATIVE ORIENTATION:

$$r(\underline{\Theta_{i-1}}, B_i, \Theta_i) = 0$$
$$t(\underline{\Theta_{i-2}}, \underline{B_{i-1}}, \underline{\Theta_{i-1}}, B_i, \Theta_i) = 0$$

TRIPLET ORIENTATION:

$$r(\underline{\Theta_{i-2}}, B_{i-1}, \Theta_{i-1}) = 0$$
$$r(\Theta_{i-1}, B_i, \Theta_i) = 0$$
$$t(\underline{\Theta_{i-2}}, B_{i-1}, \Theta_{i-1}, B_i, \Theta_i) = 0$$

Fig. 1. Bridging formulations.

(1982) mention triplets, too, for OLT. These three types of bridging formulations are symbolically exhibited in Fig. 1. The number of conditions as well as their interrelations indicate the quality of the formulation.

As both the operational and methodological benefits of simultaneous solutions are obvious, it is hoped that all manufacturers of analytical photogrammetric systems will soon have incorporated at least some sort of scale-restrained orientation procedure.

*3.2 Modes of real-time routines*

A real-time routine constitutes an endless program loop in which input values are requested from rotational or linear encoders, transformed according to some defined mathematical relationship, and transmitted to servo motors for positioning, e.g., the photo stages. Representing the essential measuring feed-back loop that comprises the human operator as primary component, the real-time program typically runs at frequencies of some 50 Hz. The input controls are usually realized by two handwheels and one foot disk as principal interfaces to the tactile senses of the operator.

In a normal mode of operation the basic real-time routine is used in a so-called *plotter mode*, where the input controls are identical to the model coordinates. By way of contrast, interior and relative orientation are performed in a *comparator mode*. Here, the manual control of measurements is achieved by the $X$- and $Y$-handwheels directly controlling the image coordinates in both photographs. When engaging a special foot switch (Kratky, 1978) or an equivalent manual toggle switch, the same handwheels operate in parallax mode, i.e. they directly control the image coordinates of one photo only, either the left or right one. As Kratky (1978, 1980a) has outlined, the $x$-parallax handwheel control may be substituted for by the $Z$-foot-disk, or both can be used concurrently, see Figs. 2 and 3.

This latter modified comparator mode (Kratky, 1978) can be advantageously applied to the bridging process, and it is denoted here by *joining mode*. The joining mode retains the illusion of a stereo comparator operation

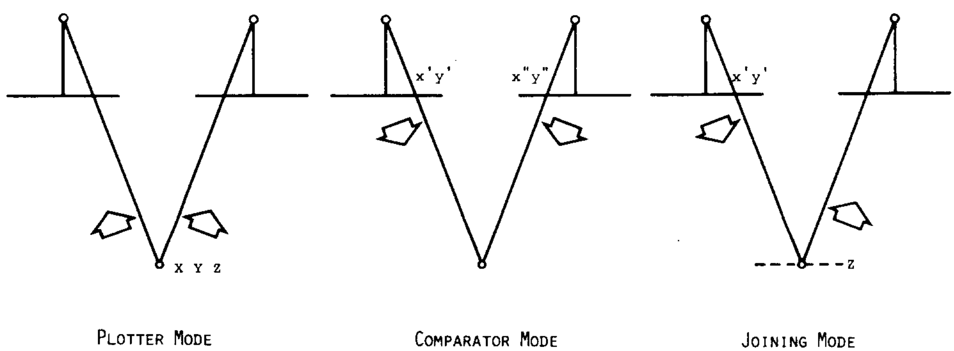



Fig. 2. Real-time modes (input controls).

| Real-Time Mode | Parallax Switch | | | | | |
|---|---|---|---|---|---|---|
| | Disengaged | | | Engaged | | |
| | Handwheels | | Foot Disk | Handwheels | | Foot Disk |
| Plotter | x | y | z | - | - | - |
| Comparator | x'=x" | y'=y" | (x") | x" | y" | - |
| Joining | x'=x" | y'=y" | z | x" | y" | - |

Fig. 3. Function of input controls depending on real-time mode and parallax switch.

by transferring the values of the *X*-*Y*-handwheels directly to the fixed old photograph. This is necessary in order to establish the given positions of any tie points measured in the preceding model. The corresponding planimetric model coordinates are then determined through a given *Z*-value entered from the foot disk. In other words, since it is the image coordinates that have to be preserved from the previous picture, the real-time routine must contain image coordinates as its primary input. The image coordinates for the dependent new photograph are finally derived from the known model coordinates.

This joining mode guarantees an optimal connection of successive photographs. Analytical systems with a primary real-time routine in plotter mode only are restricted theoretically to independent model bridging. However, computer-controlled positioning by model coordinates has a deteriorating effect on ties, the reason being that the same tie point in two joining models always gives rise to slightly different spatial positions, as these were independently derived from different least-squares calculations. Consequently, if the operator would not stick exactly to the spatial positions established in the previous model, the ties would be distorted. Yet, if done so, the real-time program does not hold in the current model, and the discrepancies may easily become visible. One can safely state that this is a serious matter, and that it has neither been given thought nor taken into consideration by the majority of the manufacturers of analytical photogrammetric systems.

The designers of the bridging software for a particular manufacturer must have realized this during program development. They tried to circumvent the obvious problem by forcibly holding the ties with the help of, though stochastically unfounded, large weights. Of course, all *x*-parallaxes could then be suppressed, but at the expense of unreasonably large *y*-parallaxes into which all computational freedom can drain. Such a solution not only is bad from the operational point of view, but is functionally and stochastically outright wrong.

### *3.3 Transformations*

According to Helava (1980), transformations are computations between different sets of coordinates, based on a mathematical relationship. By representing one of the most important software features of analytical plotters, transformations are defined between the essential mensuration and observation components of the machine as well as the physical object environment. This definition embodies corrections due to physical reality as opposed to the assumed idealized mathematical models; see also Kratky (1980a). Although needed for analytical triangulation in general, not all of these transformations are immediately relevant to OLT. In order to facilitate on-line data processing, particularly on-line adjustment, all coordinates should be referred to Cartesian basis systems. This concerns also the object coordinate system.

Basically five transformations must be distinguished in OLT, viz.:

(a) from real stage to ideal stage and vice versa;
(b) from ideal stage to real image and vice versa;
(c) from real image to ideal image and vice versa;
(d) from ideal image to regional Cartesian and vice versa;
(e) from regional Cartesian to Geodetic and vice versa.

The ideal stage coordinates are referred to a Cartesian system rigidly fixed to a particular photo stage. This coordinate system should always be considered as reference basis for all other computations. The definition of an ideal stage is necessary since the real-stage coordinates are perturbed by mainly deterministic hardware/machine systems errors, e.g. in the encoders. As the final accuracy of an analytical plotter is directly dependent on the fidelity of the employed corrections and the physical stability of the hardware, this transformation has to be provided by the manufacturer by all means. It is good to know that corresponding calibration routines are available in practically all analytical systems. However, certain mechanical instabilities in systems using rotary encoders as basic mensuration units may not be appropriate to generate confidence by the users. It should definitely be considered mandatory for all first-order analytical photogrammetric systems to have linear encoders incorporated.

The image coordinate system is assumed to be rigidly attached to the photograph, and thus has to be defined unambiguously by the positions of the fiducials or a réseaux. The real photo is warped due to film deformation and so is the real image system which, in addition, is further perturbed by lens distortion. Through its fiducials or réseaux, the real image is related to the ideal stage by means of the process of interior orientation. The ideal image is supposed to represent the situation during photographic exposure through a nondistorting lens; it is thus free of image deformation.

As the fiducials and the réseaux crosses are known with regard to their nominal, i.e. ideal positions from camera calibration, the transformation from real to ideal image immediately succeeds the inner orientation. In the most common case of four fiducials, the transformation can only be performed approximately yielding unknown systematic residuals. Nevertheless, ideal(ized) image coordinates are required for the best possible determination of the corresponding spatial bundles of rays.

Despite the obvious postulation of a rigid connection of the image coordinate system to the photograph, it is not clear at all if the existing analytical systems make consistent use of this fact. None of the known manufacturers explicitly states whether the image coordinate system is referred to always exactly the same positions and sequence of the fiducials, or only to, say, from left to right and from down to up, as seen from the operator through the eye pieces. This situation may be irrelevant as long as only one and the same strip is concerned. However, the photographs being rotated by 180° every other strip, the image coordinate system must be considered rotated, too, on the photo stage. The problem may be even more aggravated for image rotations of some 90° during a cross-tying procedure (Kratky, 1982c; Turner, 1982: see Fig. 4). In order to consistently apply this transformation, one or two reference features must be available on each photo frame. As soon as the system has successfully established the reference, perhaps under the guidance of the operator during inner orientation, it can alone locate the fiducials in a unique and unambiguous order of sequence.

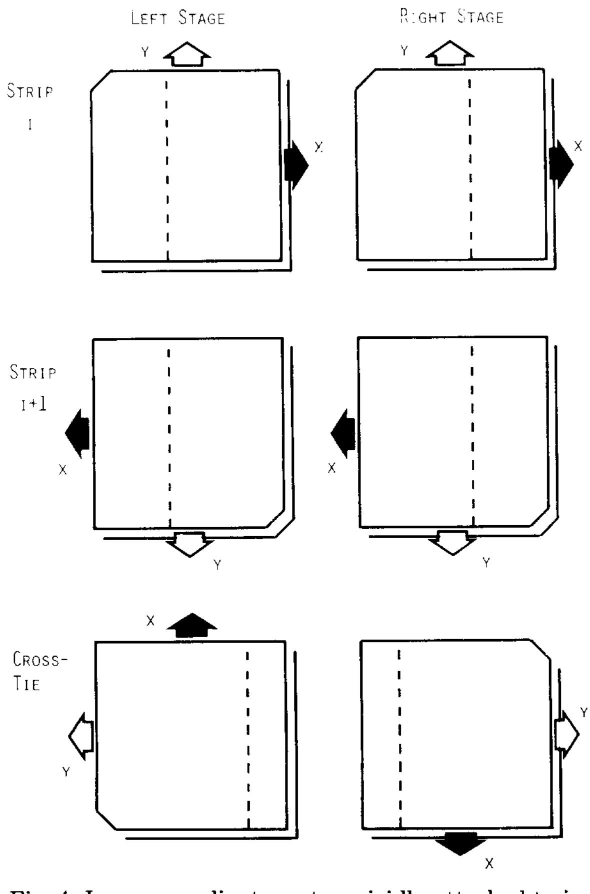



Fig. 4. Image coordinate system rigidly attached to image.

Unless independent model triangulation or block adjustment deliberately is desired, separate model coordinate systems are not needed in OLT. Like in off-line bundle block adjustment, image coordinates should directly be referred to object coordinates. This transformation, though, must be preferably expressed in terms of a regional Cartesian coordinate system, because only then can central perspectivity, represented by the collinearity principle, correctly be applied. A factor limiting the attainable accuracy is the uncertainty by which atmospheric refraction can be introduced. Theoretically, it can only be approximated iteratively. Regional Cartesian coordinates are free of the distortions inherent in map projections or geodetic systems, particularly within larger areas. The most significant distortion being earth curvature, a rigorous transformation of ground control coordinates, known for a particular project, from the geodetic to a suitably defined Cartesian system should by all means be carried out off-line and prior to OLT. Unfortunately this may only be possible on an iterative basis for partial ground control.

The on-line transformations for OLT can be summarized by four main functions, viz. calibration, interior orientation, image deformation, and perspective. These four transformations are steadily applied back and forth. Prior to recording, the functions are applied directly, i.e. the coordinates are corrected from real to ideal, and prior to positioning, they are applied inversely, i.e. the coordinates are de-corrected from ideal to real. It is not obvious if all present analytical photogrammetric systems comply to this simple rule. Kratky (1980a) describes a three-level correction system for the analytical plotter system at the National Research Council of Canada.

In a good OLT-system the coordinates referring to all ideal coordinate systems should be made available to the operator in a simple and user-friendly manner. In addition, all transformations and corrections should be applied as rigorously as is possible with the given data in order to ensure maximal correspondence between physical reality and computational ideality. This is particularly true if the final results of OLT are to be utilized directly, perhaps after an on-line adjustment. If, however, OLT is supposed to be used only as a data collecting facility for later off-line block adjustment, then recording of unbiased, only partially corrected image coordinates is advisable, viz. ideal stage coordinates. The reason stems from the fact that the off-line user generally wants to have the freedom of choosing his own corrections, especially in the context of solutions permitting additional parameters. In this way, the ideal stage coordinates are equivalent to stereo comparator coordinates in a traditional off-line photo triangulation. Thus the various on-line transformations would have to be considered temporarily only.

On the other hand, if all on-line transformations were applied correctly, ideal image coordinates, or even model coordinates derived from them, could be used for subsequent off-line block adjustment as well. Without self-calibration the adjusted results must then become better when compared to those with the use of ideal-stage coordinates. And with the self-calibration only a different, perhaps smaller set of additional parameters will come out yielding identical results.

In order to be able to re-establish a particular situation at some later stage, for each processed photograph all pertinent information gathered or computed during OLT must be saved and properly stored in data files. This concerns not only the coordinates of the measured fiducials, but also the various transformation parameters with the exception of inner orientation (Kratky, 1982c).

A transformation of object coordinates from the regional Cartesian to the geodetic system is only necessary if the result of OLT is considered final. In this case, however, not only all triangulation and auxiliary points must be transformed but also all exterior orientation parameters such as camera stations and rotation matrices. If an off-line adjustment is to be performed, the transformation must be delayed.

### *3.4 On-line block adjustment*

The ultimate goal of OLT is a solution in which the adjusted coordinates of all triangulation points of a particular photogrammetric block are readily available as soon as the measurements in the last photograph or stereomodel of the block have been terminated. This would entail that any errors and blunders detected during the triangulation process were corrected or eliminated by means of the same procedure. In other words, repeated rigorous (brute-force) or sequential runs of a corresponding on-line adjustment program would be required.

As fascinating and intriguing such an ideal approach might be, the computational and storage requirements for the continuous updating of a steadily growing number of triangulation points and parameters would be excessive. This has been clearly demonstrated by Dowideit (1980, 1982), who arrives at the impracticality of the solution at the currently available state of technology. Although the limitations seem to come primarily from hardware, many fundamental problems still encountered in finding and establishing suitable functional solutions cannot be disregarded. Molenaar (1983) in a profound study, e.g. discusses in detail several theoretical aspects of sequential processing and dynamic adjustment pertinent to photogrammetric bundle blocks. Dowideit (1980) suggests a recursive formulation based on the Bayesian estimator. In principle, this is nothing but a sequential conditional adjustment where all parameters are treated as stochastic variables with known a-priori statistics, and corresponds to a discrete Kalman or optimal filter (Dorrer, 1981; Molenaar, 1983). As Grün (1981, 1982c) has indicated, however, the concept of a Kalman filter that originally was designed for the continuous updating of a state vector of constant size, is contradictory to OLT for which a state vector of varying size is characteristic. Grün therefore suggests the use of a triangular factor update technique for sequential estimation, however for the on-line adjustment of double or triple triplets as smaller computational units rather than for entire blocks.

The present opinion seems to be against a complete on-line block adjustment. Both, Grün (1981, 1982c) and Kratky (1980b, 1982a), justly advocate a clear separation of on-line triangulation and adjustment. If quality control is considered the primary purpose of OLT (Grün, 1981), the recursive treatment of complete blocks actually is unnecessary. Smaller computational units such as triplets in a strip, or double triplets comprising two strips become relevant. This will be discussed more detailed in one of the following chapters. Full block adjustment does not seem to benefit from an on-line operation, and should therefore be done off-line (Kratky, 1980b, 1982a).

## 4 COMPUTER-CONTROLLED POSITIONING

One very essential advantage of the analytical stereoplotter lies in its fast and automatic, i.e. computer-controlled slewing capability to positions of the photo stages defined by their coordinates. From the operational point of view, rigorous and correct use of this valuable feature can speed up OLT considerably. In fact, the operating procedures of all present analytical systems make extensive use of computer-controlled positioning in one way or another. The simplest way provided by all manufacturers is a sort of semi-automatic slewing for which the target coordinates or point id-numbers have to be entered manually, and a "MOVE TO" or "VISIT POINTS" command be given. Fully automatic slewing within more complex programs, e.g. bridging, make higher demands on the software designer. It is therefore not surprising that only very few of the existing analytical systems apply computer-controlled positioning for OLT in a well conceived and user-friendly way.

While almost all manufacturers provide some kind of automatic slewing to standard patterns of points for relative orientation or to some of the given control points for absolute orientation, thus speeding up this frequently occurring yet annoying process, varying solutions are offered for the bridging task. The spectrum of these solutions ranges from bad to excellent. The operator, however, will only tolerate a solution that allows him to gain control over the computer positioning whenever he considers it necessary. This is a matter of relative orientation, where the operator always may change the position "suggested" by the computer. However, this is not so obvious for the transfer of tie points during bridging.

Generally, computer-controlled positioning in OLT plays a very significant role for tying models and strips, and it is useful for point identification both during the measurement of any control points and for editing purposes.

### *4.1 Tie point transfer*

In any type of photo triangulation, tie points are essential for establishing both good fit and continuity between successive stereomodels or adjacent photographs in a block (Kratky, 1982c). Due to generally 60% overlap between adjacent aerial photographs within a strip, successive stereomodels generate a common zone of some 20%. In this zone tie points selected and measured in the previous (old) model can be re-established exactly in the new model on the common photograph. During the change from base in to out or vice versa, this photograph remains on its stage, hence points with known image coordinates can be positioned under computer-control and at any time.

In the previous or old model the tie point was a "new tie point", becoming an "old tie point" in the current or new model. Together with other tie points, it contributes to the connection of the two models, expecting from the operator to clear any observed parallax by shifting the "new" photograph. Obviously, the simplest and most ergonomic parallax removing device consists of a special parallax foot switch (see Fig. 3). It should be controlled by the real-time program such that, when engaged, only the dependent (new) photograph is allowed to move under the control of the handwheels, the other photograph being rigidly locked. Dependent only on the base in/out flag and on the magnitude of the current image coordinates of the tie point, the dependent (new) photograph can be unambiguously specified. This simple fact is realized only in a few existing analytical systems, viz. those explicitly offering a special bridging program mode. In these operating procedures the guiding property of the computer-controlled system has been fully exploited for the benefit of the entire operation. All other systems leaving too much freedom and option to the human operator during the bridging process, are actually asking for trouble.

The accuracy of such one-sided parallax measurements primarily depends on the stereoscopic acuity of the operator, particularly regarding $x$-parallax. Although for the operator more demanding than monoscopic or stereoscopic coordinate measurements, one-sided parallax measurements are possible even if exactly defined points cannot be found, as long as image detail with sufficient contrast is present. For the operator, parallax is cleared, i.e. the measurement is finished, as soon as he perceives the floating mark to be in contact with the three-dimensional model. This should preferably be some natural detail on the photographs, a fact that has been clearly recognized by various authors, e.g. Kratky (1982c), Grün (1982a, b, 1983), Liao (1982) and Dorrer (1981). In essence, this means that, for the tying of successive models or photographs within a strip, any kind of physically marked artificial tie points is obsolete. OLT tie points are "marked" purely digitally and can thus be exactly re-established within the limits set by unavoidable instabilities of the computer-controlled stages and the film material.

It is extremely important that the operator be allowed to release the computer position-holding function by a programmed switch. If, e.g., there is a speck of dust or a scratch or other imperfection on the emulsion right on the location a parallax measurement is to be carried out, freeing the enforced control would permit the operator to move the floating mark slightly aside. Upon recording of the coordinates, the displacement has to be automatically compensated for (Kratky, 1982c), a feature found only in one particular system. Of course, the floating mark must not be moved away too far from the exact computer-holding position, depending really on the local terrain slope. However, moving away just a few microns could do a miracle, and the operator feels comfortable again. Therefore, the operating procedures should provide the flexibility of overriding computer control.

While one-sided parallax measurement is typical for "old" tie points, "new" tie points and all other point types should be measured with both stages free to move. In these cases, computer-controlled slewing usually yields only approximate or suggested positions, depending on the accuracy of the known coordinate information. It is logical that new tie points be positioned according to some pre-selected pattern similar to relative orientation.

One of the most cumbersome activities in off-line triangulation is the identification and marking of lateral tie points between adjacent strips. According to Liao (1982) and Kratky (1982c), however, the connection of strips in OLT can be achieved with digital point transfer as well. This is possible within the common zone of some 20% sidelap between adjacent photographs in two neighboring strips. The stereopairs are formed with base lines perpendicular to the strip direction and with roughly twice the magnitude of the normal base lines.

In normal operation, all photographs are measured along strips. During this bridging process all lateral tie points are considered new tie points in all photographs. It is advisable to select the lateral tie points according to a well-designed pattern. When all strips are measured, the number of lateral tie points has doubled. The actual strip- or cross-tying has to be carried out along cross-strips with 20% overlap. Inserted a second time, the photographs are rotated by 90° (Fig. 4), whereby all lateral tie points are now considered old tie points. They are exactly computer-positioned one after the other by a special cross-tying routine on those photographs where they were measured originally, and the operator is requested to remove the observed parallax. The disadvantage of having to insert each photograph twice does not seriously hamper OLT-operations due to the high measuring speed of modern analytical stereoplotters, and is easily compensated for by increased accuracy and higher reliability.

### *4.2 Supported identification*

The primary activity of the operator in photo triangulation, viz. precise and reliable measurement of individual points, should be fully supported and facilitated by the system's operating procedures. This means that the operator should not have to ascertain each measurement by visually checking the display output, or to enter a point identification number prior to each measurement, unless he deliberately wants to do so. Particularly the necessity of having to manually keying identification numbers forces the operator to interrupt his observational activity, thus decreasing his efficiency. In addition, human input is a potential source for blunders and gross errors, and is mainly responsible for many administrative errors encountered in off-line triangulation.

Unfortunately, the majority of the currently manufactured analytical photogrammetric systems require from the operator to enter point identification numbers. Only Seymour and Derouchie (1978) and US-2 (1983) describe a bridging mode in which id-numbers are automatically assigned to orientation points only, though changeable by the operator, and automated point numbering for projection centers and pass points (probably tie points; the author) is specifically mentioned in Kern (1983). Kratky (1982c) and Turner (1982) describe a bridging procedure in which unique identification numbers are automatically assigned to tie points as long as number and position of the points are standard.

These solutions show that at least tie-point identification numbers need not be assigned by the operator in a well-designed bridging operating procedure. As these make up for the bulk of triangulation points, not only considerable time may thus be saved during bridging, but also numbering errors cannot occur anymore.

Dorrer (1981) proposes a method for computer-controlled positioning and identification by means of rigorously utilizing any a priori known statistical and functional information of the points to be measured. The better this information, the better positioning and identification for a particular point. This method may therefore be used for control points as well.

From a general operational point of view, another method described by Ellenbeck (1983a, b) has found practical application. It is based on a preliminary measurement of all triangulation points on photographic prints with the help of a graphics tablet. By means of a specially developed interactive data acquisition routine, the coordinates can be rapidly measured with an accuracy of 0.5—1 mm. In addition, all ties between models and with the given control can be checked for plausibility. This type of preparation of a sort of triangulation data base (Dorrer and Kröll, 1982) has the advantage that point identification numbers need only be entered once and specifically on a rather inexpensive off-line workspace. In the analytical plotter, computer-controlled positioning and identification can then be exploited to its fullest extent. Experience has shown (Ellenbeck, 1983b) that the efficiency of photogrammetric work could thus be considerably increased. As indicated by Dorrer and Kröll (1982), this triangulation data base may very well serve as graphical interface to the human for continuously monitoring the state of the working progress.

In summary, the advantage of rigorous computer-controlled positioning and identification can be manifold. Points previously known by their coordinates can be re-visited with high precision; the actual slewing is extremely fast; operating procedures utilizing computer guidance rather than human guidance enable the operator to fully concentrate on his observation and measurement; the operator does not have to know where the floating mark is currently situated in the model; the manual or pedal controls are unambiguously locked or unlocked depending on the type of point to be measured; and no point id-numbers have to be entered in a properly designed bridging mode.

Utilization of computer-control in this way probably plays the most significant role in attaining best efficiency of OLT.

## 5 DATA COLLECTION DURING TRIANGULATION

Whether OLT is considered merely a process of data collection and preparation for subsequent off-line block adjustment, or whether it comprises online adjustment as well, the primary objective is the measurement of coordinates, and this with highest achievable precision and reliability. This entails a properly organized sequence of point measurements, optimally supported by computer-control in order to relieve the human operator of any unnecessary task. Different point types must be unambiguously identified by the computer-controlled system. The operator should have at all times the option to override the normal mode of operation and perform a different task, e.g. cross-checking or editing. In order for him to be able to monitor the quality of the collected data, effective means must be provided such as graphics displays, warning messages in case of large discrepancies, and a comfortable data-base management system for any kind of user-friendly editing purposes.

### *5.1 Organization of point measurements*

The efficiency of a data-collecting scheme is largely dependent on the skilfulness by which the point measurements are organized. Designing corresponding operating procedures is a non-trivial and by no means straightforward task, for which a multitude of possible solutions can be perceived. Depending entirely on the general ergonomic philosophy of the manufacturer, i.e. what priority he is willing to concede to the man/machine interface, the spectrum may again range from practically ideal to rather unacceptable solutions.

As Dorrer (1981) has shown, the orientation of stereopairs represents the fundamental process in phototriangulation, and is therefore an integral part of it. In this context orientation also covers scale transfer between successive models. Unlike to analog phototriangulation, however, scale transfer should rather be considered as a tying procedure for the connection of adjacent photographs both along and across the strip direction. Separation between relative orientation and scale transfer within strips yields an antiquated solution with rather annoying side-effects. From a theoretical and modern operational point of view, only some kind of scale-restrained relative orientation is acceptable (Kratky, 1980a; Kipelä et al., 1982; Radwan et al., 1982). Interestingly only one of the presently manufactured analytical systems provides such a combined solution, although various research institutions have them (see also Fig. 1).

There are two types of phototriangulation points, viz. *tie points* for connecting adjacent photographs, and *control points* for connecting the photogrammetric network with the actual object. In the course of OLT each of these two point types must be subdivided into "old" and "new" points, depending whether they have been measured before or not. Hence, four point types can be distinguished, viz. old tie points (OTP's), new tie points (NTP's), old control points (OCP's) and new control points (NCP's), see e.g. Dorrer (1981). No other points are needed for OLT. However, provision must at least be made to consider so-called *pass points* (PP's), i.e. points required to passing control information onto later stereo compilation, and *auxiliary points* (AP's). Separate *orientation points* (OP's) for the sole purpose of relative orientation are required only if they cannot be subsumed under tie points. None of the existing analytical systems specifically refer to this significant finding, though. The perspective centers, needed for independent model triangulation, are part of the orientation parameters, and should therefore not be taken into account. The task of the operating procedures now is to interlink these triangulation points to a logical and obvious sequence of steps, at the same time presenting to the operator, so to speak, a supervised guiding tour through the entire mensuration phase.

First of all, the question whether there should be a varying or constant number of tie points per model or per photograph, or whether there should be a regular pattern of tie points used or not, is a crucial one. Of course, from a general point of view a variable number of tie points may be desirable, but would inevitably lead to organizational programming difficulties due to technical restrictions, e.g. memory requirements. Operationally, a constant though selectable number of tie points is much easier system-controlled and to be remembered by the operator. This may become irrelevant, however, for more advanced systems providing dynamic addressing. Nevertheless, standard triangulation schemes yield better network homogeneity, thus contributing to predictable accuracies and reliabilities. Loss of an imaginary operator's freedom to measure tie points wherever and whenever he wants, caused by its apparent constriction due to computer-guided measurement, is outweighed by increased speed and efficiency as well as — in the long run — higher user-friendliness. By leaving the decision completely to the operator, he not only has to drive to proper locations himself, but also has to enter point types (e.g. by typing a letter "T" for tie) and point identification numbers. Such an operation would for sure defeat the purpose of an efficient OLT. What seems to be needed is a certain flexibility for the location of tie points and some sort of skipping facility for a point, e.g., if it is too close to the frame. In other words, overriding computer-control is essential. Entering point type and identification by the operator can only be avoided under extensive computer guidance, unless a system provides for automatic voice recognition.

Another question concerns the actual number of tie points. Traditionally, nine regularly distributed tie points per photograph were found to be necessary and sufficient for the formation of a phototriangulation network. It was not until recently, however, that this standard nine-point pattern per photograph, which results in a six-point pattern per model, has been recognized unsuitable for OLT due to its inherent critical error transfer capability. Three tie points for the connection of stereopairs do not support adequate control of gross errors in scale transfer. According to investigations by Kilpelä et al. (1982), Kratky and El-Hakim (1983) and El-Hakim and Kratky (1982a) a tie point pattern of much higher density is essential in order to guarantee higher reliability. Optimal patterns both from the aspect of operation and quality control should contain between 12 and 15 tie/orientation points, with clusters of two tie points each in the model corners. It is, of course, wise to choose identical tie points for both along strip-ties and cross-ties. Following Kratky (1982c), the number of cross-tie points may double in the worst operational case, although this is not too serious due to rapid computer-positioning.

Operationally, a pre-specified and henceforth constant number of tie/orientation points is always rather transparent to the user and easy to remember. Particularly regular patterns of points can then be pre-driven automatically. Here granting complete freedom to the operator in finding such a point or just its approximate location within the pattern, would be a waste of effort, as automatic positioning is much faster even if the hardware provides for a rapid handheld cursor free movement.

The following description of a somewhat ideal sequence and organization of point measurements for OLT is the outcome of consistent considerations of the previous sections of this paper. Only few of the existing OLT-solutions come close to it, the majority lagging more or less far behind in terms of good operational design, theoretical rigor and consistency. It is envisaged that contrary to Grün (1982a, b, 1983) only 20% sidelap will be used in OLT-practice, that tie points will not be marked artificially, that computational quality checks will or can be made as often as it is feasible, that the available hardware will not deviate substantially from present technology, and that approximate image coordinates of all control points and other points are known, e.g. according to Ellenbeck (1983a). See also Fig. 5.

Prior to beginning the data collection function of bridging, the first stereomodel has to be set up, either as a relatively or as an absolutely oriented model depending on the information available. The first model of a strip is the only model set up during bridging where both photographs are oriented simultaneously. The program has to lead the operator through the orientation by automatically positioning all relevant control as well as orientation and tie points. There are no "old" points in the first model of a strip, hence computer-controlled positioning of control points is only approximate. Ac-

| POINT TYPE | HUMAN | |
|---|---|---|
| | PERCEPTION | SENSE |
| OTP | OLD STAGE LOCKED ON EXACT POSITION | TACTILE / VISUAL |
| OCP | CYCLIC SLEWING AROUND EXACT POSITION WITH TYPICAL SIGNATURE | VISUAL  |
| NTP / OP | AFTER OCP'S OR OTP'S BOTH STAGES FREE AT SUGGESTED POSITION | TACTILE / VISUAL |
| NCP | CYCLIC SLEWING AROUND APPROXIMATE POSITION WITH TYPICAL SIGNATURE | VISUAL  |
| PP | DIFFERENT TONE AT SUGGESTED POSITION | AUDITORY ; VISUAL |
| AP | FREE | AUDITORY |

Fig. 5. Computer-guided measurement and human perception of point types (a proposal).

cording to the selected triangulation point pattern, the program suggests a schematic position for each orientation/tie point (NTP or OP). With both stages free to move, the operator recognizes the "new" point type character, he looks for suitable setting detail nearby, and measures the image coordinates by clearing parallax. The sequence of points generally is in flight direction (from left to right), although another sequence, viz. starting in the corners, then systematically densifying until all points are measured, would be better from a general point of view. In this case, already after five points a rather reliable relative orientation could be computed.

"New" control points (NCP's) in the first model can be approximately computer-positioned. Ergonomically, a cyclic slewing around the point with a signature typical for NCP's (e.g. circle) would represent an acceptable solution, as the operator could immediately recognize the point as control point. No entering of id-numbers is required. The program should be capable of determining an optimal absolute orientation depending on the information available. This may considerably facilitate any later quality checks. Although the first model has been oriented by now, the operator should be allowed to measure additional points, such as pass points for stereocompilation or auxiliary points. The program could indicate this by means of a different auditory signal.

The measuring procedure in successive stereomodels is primarily governed by exact computer-positioning of those triangulation points that are common to the previous model, i.e. situated on the common (now: old) photograph. Here, for "old" tie points (OTP's), the program will return to the exact position of the point on the old photograph as previously measured in the last model. This is accomplished in joining mode using the same image coordinates for this point. The "old" character of the tie point will be immediately recognized by the operator, because the old stage is locked at the exact position, the handwheels controlling the new stage only. "Old" control points (OCP's) should be automatically positioned as well, but rather in comparator mode than joining mode, the reason being that control points usually are exactly defined on the photographs. In order to indicate that a control point is to be measured, the program could cyclically slew around the exact position with a signature typical for OCP's, e.g. a cross.

The measurement of NTP's and OP's is identical to that described for the first model. The new photograph should be oriented with respect to the old photograph by means of at least a scale-constrained relative orientation in which all six orientation parameters are determined simultaneously. Any appearing NCP's should automatically be used to up-date the current strip adjustment parameters. Due to the complexity of block adjustment, cross-ties between strips cannot yet be considered and each strip is treated individually. Since strips in general are not adequately controlled, the strip coordinate systems may considerably vary in orientation.

Probably the currently best method for cross-ties between strips of 20% sidelap is due to Liao (1982) and Kratky (1982c), also described by Turner (1982). It is a compromise between a purely theoretical approach and an operationally still acceptable solution. After the strips have been formed, the cross ties can be measured by forming stereopairs from photographs belonging to adjacent strips by rotating the base by 90°. This means that either the photographs are inserted with 90° rotation, or the optical systems are rotated. The measurements take place in comparator mode, as the search for cross-ties is limited effectively to the 20% area. Any point in the sidelap area which has been measured as tie or orientation point during bridging in either of the two strips, now is considered an OTP, any control point an OCP. The point thus can be automatically positioned exactly in either of the two pictures. The corresponding stage being locked, the operator clears parallax by moving the other stage. First, all tie points are transferred from strip 1 to strip 2, then vice versa, with the possibility of skipping since not all points may be needed. The operator should also be allowed to measure additional points, although such a point would not strengthen the tie very much. OCP's lying in the sidelap area can be treated similarly.

If the actual cross-tying is performed along-strip, the connection between the two strips could be controlled on-line, however, at the expense of having to insert each photograph a third time. The aforementioned investigators, therefore, use cross-tying along cross-strips perpendicular to normal strips. From the operational point of view it is important that the operator does not have to know anything about the measured point. It is amazing how simple, straight forward and fast this method is, particularly for photogrammetrists still thinking in terms of off-line phototriangulation with artificially marked and transferred points. In fact, the operator in the OLT-system just pushes buttons or switches and measures. The point to be measured appears in the field of view, and the stage having been computer-positioned exactly will be automatically locked. The operator, using only the two handwheels, measures on the free stage, be it left or right. The simplicity of such an operation, however, depends entirely on the ergonomics of a corresponding well designed non-trivial operating procedure.

In order to round this section off, a real yet operationally far less pleasing bridging solution will be described in the sequal, somewhat representative to the majority of existing methods not utilizing a specific bridging mode. Assuming a photograph not being the first one in a strip, the operator has to manually activate the RELATIVE ORIENTATION routine. In comparator mode, this program will automatically position all points known from the previous model, viz. exactly on the old, and approximately on the new photograph. Whether only OTP's may be processed in that way or not is unclear. The point identification number will be displayed on the control panel. Interestingly, the operator may tentatively skip any point that might be measured with greater ease in plotter mode later. This feature in fact is a nuisance.

NTP's must now be identified, located, positioned and stored manually, as no provision is made for a regular point pattern. Auxiliary points such as control points may be measured as well. The operator may now actuate the computation of the relative orientation (five parameters only), thus creating a stereo model. This model could be saved on file as independent model for later block adjustment. It is, however, more likely that the ABSOLUTE ORIENTATION routine will be activated for checking scale transfer and other control. The program first displays all previously measured tie and control points, then automatically positions previously "skipped" points to be measured now (or not) by the operator. The model scale is determined with the aid of all OTP's; however, all these points, and perhaps control points as well, had to be stored manually in the control-point memory under their negative (!) identification number during absolute orientation of the previous model. It is clear that this pretended "flexibility" actually is more disturbing than operator-friendly. If the quality of the scale transfer has been accepted by the operator, the program searches for real control points and calculates an absolute orientation.

Obviously, the organization of point measurement as described here is rather discouraging, and actually defeats the purpose of OLT. The solution is unacceptable from the point of view of both modern ergonomics and mathematical-theoretical rigor. The various triangulation point types are not distinguished consistently enough, and practically only independent models can be processed adequately.

### 5.2 *Editing facilities*

One of the primary objectives of OLT is to systematically collect and generate photogrammetric data that are both precise and reliable. Being essential component of the computer-supported mensuration system, the human operator interacts with the machine through visual, auditory and tactile interfaces. As nobody can expect him to be completely immune to errors, blunders or mistakes even in the best conceivable operating environment, a wide variety of data-editing functions must be considered absolutely necessary and be incorporated right from the beginning. From an ergonomic point of view, these functions may be realized either as special function keys on a control panel or on the general key board, or as special commands on the key board in editing mode. These possibilities are offered by the presently manufactured analytical systems in one way or another.

Fortunately, the majority of errors occurring during a measurement usually are recognized by the operator immediately after they have appeared, e.g. not precise point setting or parallax removal, wrong point id-number or point type input. Although sophisticated OLT-systems automatically generate id-numbers, thus relieving the operator from having to enter them, he must have the option to RENUMBER a current point id-number, or to RETYPE (i.e. to change) the point type. The simplest form of data editing can be applied at the basic level of point measurement (Kratky, 1981). Of significance is a CANCEL function for cancelling the last point measured (i.e. recorded) from the point list. This rather convenient function should be repeatedly applicable to all records of the list according to the LIFO-principle. In some systems an equivalent REJECT function is used. Wrongly cancelled records should, however, not be considered lost but rather be allowed to be re-established by a RECALL function.

Only one manufacturer of analytical systems provides for repeated measurements of points other than just double measurements. As this operation is so fundamental for any kind of mensuration system, it should not only be combined with a sequential AVERAGE function but should also be controlled by means of a special switch in easy reach of the operator's hands close to one of the handwheels. This feature permits a certain pre-selected level of precision to be achieved any time the operator thinks it necessary. REMEASURE could be used for a complete new measurement either of the last point — if not specified — or of any point specified by its id-number, the point to be remeasured being computer-positioned, of course. Also, SKIPing a computer-positioned point may be of some advantage in bridging.

As has been shown by one particular manufacturer, consistent use of alphanumeric string data can make the editing process extremely simple and useroriented, as other data for explanatory purposes may be added arbitrarily. This, however, requires the utilized high-level programming language to provide conversion capabilities from string to numeric data and vice versa.

DELETE is mostly used for completely erasing a specified record from a point list. Its complement, viz. INSERT is convenient, too, although not offered in most systems, as new point data may also be ADDed or APPENDed to the existing point list. For the operator, consistency in the usage of these high priority editing functions is of utmost significance. Each function must exactly and unambiguously specify one and only one action including, however, any interdependent consequential actions. If, e.g. a record has been deleted from the current point list, all previous computations depending on the contents of the list must be automatically repeated without the deleted point. Editing procedures not providing intermediate exits to other modes would have to make the operator responsible for additionally activating successive functions, although a computer-controlled solution could easily be programmed. One particular analytical photogrammetric system has solved this obviously frequent task by providing special ABORT and RECALCULATE functions. All others expect the operator to re-start computations from the beginning. In using functions such as REMEASURE, DELETE, ADD (APPEND; INSERT), DISREGARD or INCLUDE, one should therefore exercise caution and not try to enforce an unrealistic fit by excessive or biased corrections. According to Kratky (1981), the process must be reserved for the elimination of gross errors only.

The on-line editing capacity is essential for OLT, because it practically can completely eliminate any gross errors in the data material. This is particularly so if the data are, in addition, continuously quality controlled by means of efficient functional and stochastic computer-supported data snooping techniques. The beauty of on-line and interactive methods is that they inherently are error-and-trial oriented, a typically on-line feature completely unknown to off-line systems.

Legitimate suspicion for erroneous measurements in a previous stereomodel necessitates a MODEL RESET function in order to re-establish the former state of the model. The current model data must then be saved temporarily with the help of a complementary MODEL SUSPEND or MODEL HOLD function. Resetting a model means that the process of interior orientation has to be performed anew, contrary to a simple MODEL RESTORE which would only undo the present model suspension assuming the photographs having remained on their stages; see Kratky (1982c, 1981), also US-2 (1983).

Data editing could be enhanced by on-line computer graphics, as was suggested by Dorrer and Kröll (1982). However, this necessitates rather sophisticated operating procedures and latest hardware technology for highly intelligent graphics terminals. Nevertheless, serious investigations into the application of interactive computer graphics to OLT is advocated, as this technique could considerably improve the human interface with the triangulation data base both for monitoring the progress of work and for displaying actual residuals or discrepancies for visual quality checks.

### *5.3 Computer-assisted quality control*

Considering OLT merely as a data collection system without any checks on the observations does not fully exploit the potential of analytical stereoplotters, as it may be employed in any other type of photogrammetric instrument. Presently active investigators of OLT-methods seem to agree unanimously that for practical applications and, for the time being, the most promising approach to OLT is data collection comprising quality control and editing facilities. Complete rigorous block adjustment should still be left for off-line data processing (Grün, 1981; El-Hakim and Kratky, 1982a; Radwan et al., 1982; Kratky and El-Hakim, 1983). This significant finding should, however, not discourage from any further theoretical studies to include on-line block adjustment as well, see e.g. Molenaar (1981). At the present state of technology, however, rigorous on-line adjustment methods cannot be performed in accordance with good ergonomic and operational principles of OLT (Dowideit, 1980). On the other hand, considering the reliable error-detecting power of relatively small sub-blocks (Grün, 1981), it seems at least doubtful whether on-line block adjustment should really be incorporated as integral part of OLT. If OLT is capable of generating photogrammetric triangulation data virtually free of gross errors, the necessity of applying numerically expensive rigorous error detection methods after a large off-line block adjustment could be avoided.

Effective quality control is based on direct computer analysis of the data. In OLT this should principally be done at the earliest possible instant of time and with the least possible expenditure (Klein and Förstner, 1981). Bench marks permitting reliable data tests are depending on the configuration of the triangulation network and on the sequence of observations carried out. Thus, after each relative orientation, $y$-parallaxes can be determined, though sufficiently reliable only if considerably more than just the standard six points were measured. After each scale transfer, corresponding tie discrepancies are an indication of the goodness of fit between two models. These computational units can be combined to some scale-constrained orientation (Kilpelä et al., 1982; Kratky and El-Hakim, 1983) or to triplets (Radwan et al., 1982) in order to improve the power of the test. More complicated triangulation structures yielding effective reliability measures are investigated by Grün (1981). Each time a sufficient number of control points has been observed, preliminary strip adjustments would be able to detect possible errors on the control points as well. Generally, though, network-internal quality control for checking only photogrammetric data is much easier to carry out than external data analyses comprising control information.

A first rudimentary though operationally pleasing way of presenting the results of numerical quality control methods consists of merely displaying the residual values for each point in a list. These discrepancies may indicate if a gross error has been committed. However, in many cases it is difficult or outright impossible to locate correctly the point where the faulty observation took place. Here, a suitable graphical display of the residual vectors within the triangulation network would at one glance present a more comprehensive picture of the situation (Dorrer and Kröll, 1982). But even then, low redundancy in a stereomodel and high correlation between the residuals of certain points can give rise to inefficient or misleading results in visually locating gross errors. Both for operator and computer, detecting the existence of a gross error is easy compared to the task of locating it. It is therefore of great importance that computer-supported methods for blunder detection and location are based on sound functional and stochastic strategies. They are of little use if the operator does not gain confidence from the error messages issued by the computer. Radwan et al. (1982) state justly that, in order to achieve that goal, computations for blunder detection may not be founded on approximate methods.

Statistical error location techniques based on Baarda's "data snooping" have found wide spread application in off-line block adjustment. Based on the availability of maximum test values such as standardized residuals, the method permits the location of only one gross error per adjustment run, entailing another run to check for more blunders. Its applicability and efficiency to off-line adjustment is therefore limited, particularly when many errors are to be expected. By virtue of its sequential character, however, it is highly unlikely for OLT that more than one blunder can occur at a time. Blunder location by data snooping could therefore be applied to OLT with advantage. Since blunder location is based on statistics, the probability that a blunder was found correctly always is less than one. Hence, the operator must have the option to interpret the computer message according to his experience, and perform certain interactive data editing actions relevant to the momentaneous problem.

Many strategies for error searching in phototriangulation found necessary in off-line block adjustment (Klein and Förstner, 1981) may be considered irrelevant for OLT, the reason being that accumulation of errors hardly can occur, that wrong point id-numbers cannot appear due to automatic or a priori numbering, that practically no point transfer errors are present anymore, and that point confusions or identification errors have become rather rare. This capacity of OLT is considerably enhanced and its reliability substantially improved by using a much larger number of tie points than traditionally is recommended. This fact has been successfully demonstrated by Kratky and El-Hakim (1983) for the NRC ANAPLOT.

### *5.4 Data base generation, preparation, management and retrieval*

The memory capacity of computers is limited so that, for applications involving large data sets, the system must have a peripheral storage device. Of the two types of storage in an analytical photogrammetric system (Niedzwiadek, 1980), the temporary storage is that what makes up the main memory of the host computer, while the permanent storage has to be put on peripheral magnetic devices, e.g. hard disk. In the progress of OLT, large sets of data are collected and generated. As long as the current stereomodel is being processed, the data associated with it should definitely remain in main memory due to fast access times. Only when the operator considers this model to be complete, perhaps after some editing work, the temporary data should be saved on (permanent) file.

Although there is no set standard that determines how data are stored and retrieved, the structure of the stored data is an important consideration in the design of the software system. Therefore, the solutions adopted by the various analytical systems manufacturers can differ considerably. Guidelines for data storage and retrieval that should be observed are:
— permitting data to be collected in more than one session;
— being able to recover data in the event of a power failure;
— organizing data so that it can be easily edited or updated.
For simple applications involving a single stereomodel, data management is least complex, as all pertinent data usually can be contained in main memory and the collected point data stored on an inexpensive peripheral device. In OLT, however, where many models are involved, efficient data base management techniques are very useful. It is fundamentally important that information having the same functional purpose in the system should be organized into common storage areas. Consequently, the data ought to be organized into the following files:
— Instrument calibration data
— Camera definition data
— Fiducial coordinates
— Fiducial transformation parameters
— Camera orientation parameters
— Ground control coordinates (regional Cartesian)
— Regional Cartesian/geodetic transformation parameters
— Model coordinates
— Photo coordinates
— Lateral tie points (Kratky, 1982c).
The majority of these files are continuously generated, stored and updated on disk during OLT-operations. Since data are collected for individual models, the model coordinate file can directly be addressed with its corresponding current stereomodel. The model coordinates have to be computed from fully corrected photo coordinates after completion of any editing. The file must be supplemented by the model coordinates of the perspective centers and by identification numbers. In order to be directly applicable to bundle block adjustment programs, the organization of the photo coordinate file should be according to individual photographs rather than models or stereo photographs. Photo coordinates should be made available both in raw (i.e. only system-corrected) and in fully corrected form, depending on its later use.

The file of lateral tie points results from the identification and transferring of tie points between adjacent strips, and has to be updated in the progress of cross-tying. Its final contents must be properly transferred to corresponding model and photo files.

The majority of manufacturers use data files that are organized more or less according to above guidelines. In most cases, however, the actual data base management systems are on a primitive operating systems level rather than a user-oriented application level. Special preparation routines may be required interactively to generate true photo coordinate files from stereo image coordinate files. One particular manufacturer providing a comfortable bridging mode for OLT generates point data files somehow organized according to photo-triplets. Though perhaps beneficial for the numerical process of bridging, this organization is rather opaque for the human user.

Upon termination of OLT, the various data files consist of data that is edited, corrected, and consistently updated either for subsequent off-line block adjustment or for later use in stereo compilation.

## 6 SUPPORT OF OFF-LINE DATA PROCESSING

As OLT must be considered in the framework of a much wider range of photogrammetric work, treating it as a completely independent or isolated task would be wrong. This primarily concerns the further support of photogrammetric stereo compilation, but also the preparation of the collected data for off-line block adjustment programs.

### *6.1 Block adjustment*

Practically all manufacturers of analytical stereoplotter systems provide adequate means for a continuous transition of OLT-data to off-line block adjustment. In most cases, data files generated and updated in the progress of OLT have to be modified to meet certain compatibility conditions imposed by the applied off-line block adjustment programs. Normally, special preparation routines have been designed to reorganize the original data according to certain required different identification schemes, or to a different order of sequence. This is especially true if the model-oriented OLT-data are supposed to be processed through a bundle block adjustment program. One particular manufacturer has included automated band width minimization in his interfacing program by optimally recording the models, a feature that can considerably reduce execution times and thus improve the overall efficiency of the method (Steidler, 1983). It should be obvious that the actual adjustment is best performed with control points known in terms of a regional Cartesian coordinate system, for only such a base system can properly eliminate the need for otherwise dubiously applied earth curvature corrections. The final results of either on-line or off-line block adjustment, however, must always be expressed in terms of the actual geodetic or mapping system. The transformation not only concerns all triangulation points and auxiliary points as such, but comprises exterior orientation parameters as well. It is not known whether existing systems have taken into consideration this important point or not, important mainly for further stereo compilation.

*6.2 Stereo compilation*

Theoretically, the traditional concept of pass points necessary for supporting each individual model for stereo compilation, can be abandoned if compilation follows in an analytical photogrammetric system. This is true, since the orientation parameters determined during OLT are related to a set of image fiducial marks whose definition is superior to that of natural details, artificial marks or even field targetted points. The process of interior orientation in analytical stereoplotters permits precise reconstruction and resetting of any stereomodel by merely re-introducing the known and stored exterior orientation parameters. Practically, however, and contrary to Kratky (1981, 1982c), inevitable disturbances, caused primarily by different systems calibration errors, can occur if triangulation and compilation are not performed in the same analytical instrument. In addition, geodetic base system and model-oriented local object system never exactly correspond with each other, and the orientation parameters resulting from the adjustment of larger blocks may not be exactly compatible to those attained from the orientation of single models. Hence, there will be both random and systematic deviations between the actual model needed for compilation, and the orientation data of the adjusted photographs. Minor adjustments, to be realized with the help of pass points, may therefore not be avoided. The pass points establish a proper fit of the current state of the photographs with the photogrammetric network. No further operational delays need occur if four pass points are measured in the corners of each stereomodel in addition to the triangulation points. Pass points, though, have to be identified by natural, easily and unambiguously recognizable detail in the images. Point sketches or identification diagrams are not required if the pass points are automatically positioned during compilation. In that way computer positioning by digital data does not deviate so much as to make visual identification of a pass point impossible.

If OLT is performed in preparation for stereo compilation in analog restitution instruments, pass points are absolutely necessary, the reason being that due to inevitable instrumental errors, nominal and actual orientation settings never coincide exactly. Superimposed to the disturbances inherent in purely analytical systems, this effect gives rise to generally much larger deviations, even if the instrumental orientation parameter settings are determined by special routines, as for instance offered by a few instrument manufacturers. In order to avoid time consuming identification sketching and marking, normally required for off-line compilation, Kratky (1982c) proposes the use of réseau crosses or other artificial marks in one image only, viz. as a suitable substitute for point marking.

In principle, however, clearly defined natural pass points could be utilized the same way as in analytical stereoplotters. Provided that the analog instrument is properly calibrated, orientation parameter settings computed from adjusted triangulation data ought to be good enough to ensure that the model is approximately sufficiently re-established for visual inspection. In the worst operational case, no digital devices are connected to the analog restitution instrument, the only result being a graphical map manuscript. In order for the operator to unambiguously identify the pass points, the computer positioning potential of analytical systems must be simulated manually. Assuming that not only pass points were plotted on the map manuscript but also the two current perspective centers, the plotting sheet can be properly oriented with respect to the stereomodel. After positioning a plotted pass point, the floating mark should be so close to the corresponding model point that — even if no identification sketches are available — the operator is able to undoubtedly identify and measure the actual pass point on the images. Clusters of pass points may improve the efficiency of the method.

## 7 CONCLUSIONS AND OUTLOOK

Today most analytical stereoplotters are used as fast data collection systems for phototriangulation. For practical applications the accuracies achieved seem to be equivalent to those obtained with precision comparators. Increased constraints on efficiency and economy of OLT as well as on reliability of the collected data have put pressures on the photogrammetric end user for optimizing and improving existing methods. As drastic improvements can only be expected by consistent, hence expensive, software modifications, the manufacturing industry is rather reluctant in pushing the on-line concept very far. Presumably, the manufacturers of analytical systems are aware of the significance of this problem, but hesitate due to its complexity and because of other tasks. Unfortunately, non-transparency in the structure of presently offered analytical plotter software hardly allows for changes to be made in a reasonable period of time. On the other hand, a few solutions developed by academic research groups, e.g. the National Research Council of Canada, have demonstrated the real potential inherent in OLT and the operational advantages of a well-designed system. Apparently, the users of analytical systems are becoming aware of the necessity to fit existing programs to their needs. Therefore, access to the source code is a must for the user, and a manufacturer not disclosing his software actually is working against himself.

Under practical environmental conditions, operational aspects play the primary role to guarantee the OLT-system to function properly. By consistently making the life easier to the end user, on-line phototriangulation automatically becomes more efficient and its data more reliable. One cannot over-emphasize enough the significance of the system's feedback property and its positive psychological influence on the operator. The importance of operational aspects in practice entails that the man/machine interface should be as simple as possible. Since this is the case in a system with predefined and prepositioned points, computer-positioning is a prerequisite for a good

OLT-system. The general philosophy of a few instrument manufacturers tends to leave the operator a maximum of freedom in selecting the points to be observed, or in the choice of activating routines for data processing. In the author's opinion, this is a rather primitive solution for OLT. During the process of OLT, guidance should not originate from the human operator but from the computer. It is so much faster and more reliable. Only if the on-line concept is pushed towards its extremes, then its overall advantages as compared to off-line solutions will be obvious. This also concerns theoretical aspects of OLT such as rigorous quality control and on-line adjustment.

These statements may appear rather academic and perhaps too demanding. However, if the manufacturer is reluctant to push this concept due to limited resources, and if at the same time the end user is not strong enough to enforce it, who else than the academic group should start propagating on-line phototriangulation?

While software tends to be the bottleneck in the entire system, hardware becomes more powerful, more versatile, but not necessarily more expensive. In the course of providing a well-designed ergonomic workspace, computer graphics and voice recognition modules may be of advantage for OLT. Particularly the human auditory sense could considerably speed up triangulation operations. Yet, the computer, too, could contribute to increased efficiency, e.g. if digital image processing techniques or robotics were employed.

## REFERENCES


Amer, F.A.A.F., 1981. Theoretical reliability of elementary photogrammetric procedures. ITC J., 1981 (3): 278—307.

Blais, J.A.R., 1982. Recursive least-squares estimation using Givens transformations. Proc. Symposium on Mathematical Models, Accuracy Aspects and Quality Control, ISPRS-Comm. III, June 7—11, Helsinki, pp. 60—67.

Brindöpke, W., 1983. Experiences with bundle block adjustments for vertical control point determination and cadastral surveys in Niedersachsen, F.R.G. (in German). Presented Paper Annual Meeting DGPF, Münster.

Carl Zeiss, 1980. Operator's Manual for the Planicomp C100.

Dorrer, E., 1981. Real time orientation as integral part of online analytical aerial triangulation. Photogrammetria, 36 (3): 111—118.

Dorrer, E. and Kröll, F.S., 1982. Ergonomic aspects of on-line aerotriangulation (in German). Proc. Symposium on Mathematical Models, Accuracy Aspects and Quality Control, ISPRS-Comm. III, June 7—11, Helsinki, pp. 563—575.

Dowideit, G.R., 1980. An online bundle block adjustment for analytical plotter. Int. Archives Photogrammetry, XXIII/B3, pp. 168—177.

Dowideit, G.R., 1982. Experience with improved on-line-bundle-block-adjustment on the APC-3. Presented Paper ISPRS-Comm. III Symposium, June 7—11, Helsinki, 8 pp.

Eggenberger, O., 1983. Analytical restitution systems from the computer science point of view (in German). Presented Paper at 39th Photogrammetric Week, Stuttgart, 7 pp.

Ellenbeck, K.H., 1983a. Analytical-photogrammetric local-area network system of the state surveying office in Nordrhein-Westfalen, F.R.G. (in German). Presented Paper at 39th Photogrammetric Week, Stuttgart, 11 pp.

Ellenbeck, K.H., 1983b. Computer assisted aerotriangulation for control point determination in Nordrhein-Westfalen, F.R.G. (in German). Presented Paper Annual Meeting of DGPF, Münster.

El-Hakim, S.F., 1982. Data Snooping with Weighted Observations. Proceedings Symposium on Mathematical Models, Accuracy Aspects and Quality Control, ISPRS-Comm. III, June 7—11, Helsinki, pp. 126—133.

El-Hakim, S.F., 1983. Quality control with analytical plotters. Presented Paper at 39th Photogrammetric Week, Stuttgart, 19 pp.

El-Hakim, S.F. and Kratky, V., 1982. Quality control for NRC on-line triangulation. Proc. Symposium on Mathematical Models, Accuracy Aspects and Quality Control, ISPRS-Comm. III, June 7—11, Helsinki, pp. 134—144.

El-Hakim, S.F. and Ziemann, H., 1982. A step-by-step strategy for gross-error-detection. Proc. Symposium on Mathematical Models, Accuracy Aspects and Quality Control, ISPRS-Comm. III, June 7—11, Helsinki, pp. 145—153.

Grün, A., 1981. Reliability structures of small bundle system for on-line triangulation. Proc. ASP-Convention, San Francisco, Calif., pp. 299—309.

Grün, A., 1982a. Phototriangulation with analytical plotters using natural tie points. Presented Paper ACSM-ASP Meeting, Denver, 10 pp.

Grün, A., 1982b. Phototriangulation with analytical plotters using natural tie points. Proc. Symposium on Mathematical Models, Accuracy Aspects and Quality Control, ISPRS-Comm. III, June 7—11, Helsinki, 202—211.

Grün, A., 1982c. An optimum algorithm for on-line triangulation. Presented Paper ISPRS-Comm. III Symposium, Helsinki, 21 pp.

Grün, A., 1983. Phototriangulation with analytical plotters. J. Surv. Eng., 109/1: 6—13.

Helava, U.V., 1980. Analytical plotter basics. Proc. ASP Symposium on analytical plotters, April 20—25, Reston, U.S.A., pp. 13—29.

Hobbie, D., 1979. On-line aerial triangulation with the Zeiss-Planicomp. Presented Paper, International Symposium Current Trends in the Development, Execution and Use of Aerotriangulation, 15—17 Oct., Brisbane, Australia, 9 pp.

Höhle, J., Hügli, P. and Schaeffer, T., 1982. Control point determination with the Avioplot RAP System. Proc. Symposium on Mathematical Models, Accuracy Aspects and Quality Control, ISPRS-Comm. III, June 7—11, Helsinki, pp. 241—246.

Jones, P.F., 1978. Four principles of man-computer dialogue. Comput. Aided Des., 10/3: 197—202.

Kern, 1983. Kern DSR1.AETRI — A summary. Short description of aerial triangulation package.

Kilpelä, E., Heikkilä, J. and Inkilä, K., 1982. Some results of gross error detection tests in relative orientation and scale transfer. Proc. Symposium on Mathematical Models, Accuracy Aspects and Quality Control, ISPRS-Comm. III, June 7—11, Helsinki, pp. 622—635.

Klein, H. and Förstner, W., 1981. Strategies for Error Detection in Aerial Triangulation (in German). Schriftenr. Inst. Photogramm. Univ. Stuttgart, 7: 91—109.

Kratky, V., 1978. On-line analytical triangulation. In: ANAPLOT: History, Basic Features and Performance. NRC Publ. No. 17281, pp. 109—129.

Kratky, V., 1980a. On-line aerial triangulation on the ANAPLOT. Invited Paper, Proc. ASP Symposium on Analytical Plotters, April 20—25, Reston, U.S.A., pp. 207—224.

Kratky, V., 1980b. Present Status of On-Line Analytical Triangulation. Invited Paper, Int. Archives of Photogrammetry, XXIII/B3: pp. 379—388.

Kratky, V., 1981. Operational Advantages of On-Line Photogrammetric Triangulation. Presented Paper at ASP-Fall Convention, San Francisco, Calif., 9 pp.

Kratky, V., 1982a. Present status of on-line analytical triangulation. Photogrammetria, 38 (1): 1—12.

Kratky, V., 1982b. Report on activities of Working Group III-2 in 1980—82. Proc. Symposium on Mathematical Models, Accuracy Aspects and Quality Control, ISPRS-Comm. III, June 7—11, Helsinki, pp. 296—298.
Kratky, V., 1982c. Recent progress in the NRC on-line photogrammetric triangulation. Proc. Symposium on Mathematical Models, Accuracy Aspects and Quality Control, ISPRS-Comm. III, June 7—11, Helsinki, pp. 284—295.
Kratky, V. and El-Hakim, S.F., 1983. Quality control for NRC on-line triangulation. Photogram. Eng. Remote Sensing, 49 (6): 763—769.
Kröll, F.S., 1981. Analysis of the fundamentals for the development of interactive systems in photogrammetry (in German). Doctoral Thesis; DGK Reihe C, Heft 270, München.
Liao, Y.-Ch., 1982. Investigations of automatic point transfer for aerial triangulation with analytical plotters (in German). Wissenschaftliche Arbeiten der Fachrichtung Vermessungswesen der Universität Hannover, Dissertation, Nr. 112, 100 pp.
Masson D'autumne, G. and Giraudin, P., 1982. A universal block adjustment procedure with automatic error elimination. Proc. Symposium on Mathematical Models, Accuracy Aspects and Quality Control, ISPRS-Comm. III, June 7—11, Helsinki, pp. 354—368.
Methley, B.D.F., Elmaleen, M.E. and Abdillah, M.H.A., 1982. Some developments in analytical aerial triangulation. Photogram. Rec., 59 (10): 559—573.
Molenaar, M., 1981. Some problem areas in the field of quality control for aerotriangulation. ITC J. 1981 (3): 253—265.
Molenaar, M., 1983. Several aspects of sequential processing of photogrammetric bundle blocks. In: F.E. Ackermann (Editor), Seminar Mathematical Models of Geodetic/Photogrammetric Point Determination With Regard to Outliers and Systematic Errors. DGK, Reihe A, Heft 98, München, pp. 105—130.
Niedzwiadek, H.A., 1980. Aspects of data storage and retrieval pertinent to the use of analytical plotters. Proc. ASP Symposium on Analytical Plotters, April 20—25, Reston, U.S.A., pp. 285—289.
Petrie, G., 1983. The philosophy of digital and analytical photogrammetric systems. Presented Paper at 39th Photogrammetric Week, Stuttgart, 28 pp.
Radwan, M.M., Stefanovic, P. and Adhikary, K.R., 1982. Triplets and quadruplets in on-line photogrammetric triangulation. Presented Paper at ISPRS-Comm. III Symposium, Helsinki, 35 pp.
Rüdenauer, H., 1984. The PLANICOMP-family, its features and innovations (in German). Bildmessung Luftbildwes., 52 (1): 40—49.
Schreiber, P., 1983. Practical experiences with the ATR aerial triangulation program (in German). Wild-Heerbrugg, 18 pp.
Seymour, R.H. and Derouchie, W.F., 1978. Aerotriangulation with the US-1 analytical plotter. Presented Paper at ACSM-ASP Convention, Washington, D.C., 13 pp.
Steidler, F., 1983. Software packages for aerotriangulation from WILD (in German). Presented Paper Annual Meeting DGPF, Münster.
Turner, H., 1982. The Canadian Marconi aerial triangulation package. Presented Paper ISPRS-Comm. III Symposium, June 7—11, Helsinki, 17 pp.
US-2, 1983. Operator's Manual for the US-2; Section 13: Bridging.
Vigneron, C. and Dubuisson, B., 1979. Real-time analytical triangulation integrated into plotter on MATRA TRASTER. Presented Paper, International Symposium Current Trends in the Development, Execution and Use of Aerotriangulation, 15—17 Oct., Brisbane, Australia, 12 pp.
Würtzler, H., 1983. Critical report on experience on the 7 year work with an analytical plotter under practical conditions (in German). Presented Paper at 39th Photogrammetric Week, Stuttgart, 4 pp.