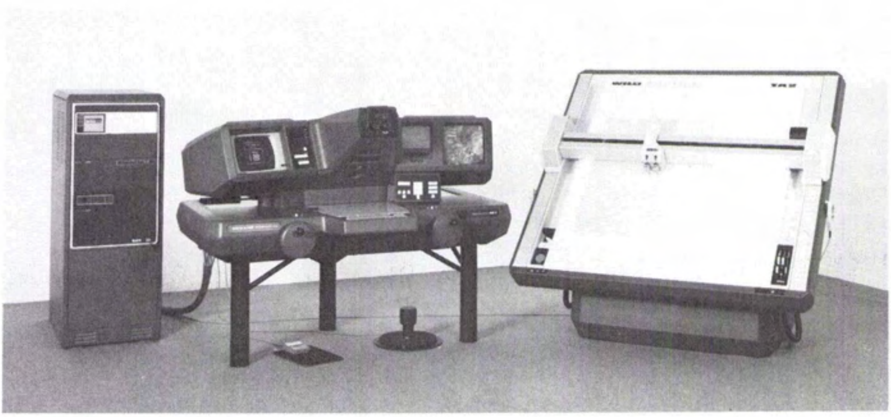

FRONTISPIECE. Aviolyt AC1 analytical stereoplotter with the Aviotab TA2 digital plotting table.

JOACHIM HÖHLE
Wild Heerbrugg Ltd.
CH-9435 Heerbrugg, Switzerland

Performance Parameters of a Digital Plotting Table for Photogrammetry

Accuracy, quality, working speed, and support by computers and software determine the use and the economics of a digital plotting table.

ABSTRACT: *Digital plotting tables are used in photogrammetry in conjunction with computer-controlled stereoplotters and interactive graphic systems. The performance parameters of the plotting table are of the greatest importance for the efficient operation of the complete system. Performance parameters such as accuracy, quality, working speed, and support by computers and software are explained. The new digital plotting table Aviotab TA2 serves as an example.*

INTRODUCTION

SINCE 1974, various manufacturers have produced digital plotting tables for photogrammetric work. At the present time, about 600 such tables are in use. The digital plotting table is regarded as one of the most important innovations in practical photogrammetry in recent years. Its performance parameters determine its use and economics. This article explains the various performance parameters of a digital plotting table. The results quoted generally refer to the new Aviotab TA2 digital plotting table made by Wild Heerbrugg.

PHOTOGRAMMETRIC USES OF A DIGITAL PLOTTING TABLE

There is a wide variety of uses in photogrammetry for a digital plotting table. The most important application is the graphic output from a *photogrammetric analog plotter*. The result is a manuscript which is subsequently enhanced by the cartographer. The "intelligent" functions integrated into the digital plotting table, such as straight-line connection and symbol generation, facilitate the operator's task and increase productivity by comparison with earlier plotting tables. In this application, the speed and acceleration of

PHOTOGRAMMETRIC ENGINEERING AND REMOTE SENSING,
Vol. 49, No. 1, January 1983, pp. 111-118.

0099-1112/83/4901-111$02.25/0

the table are mainly determined by the operator. The maximum values are not particularly high.

By the *addition of a microcomputer*, a wide range of plotting functions and the symbols and line types required in the maps can be executed. Such a system of computer assistance makes it possible for a map sufficient for planning purposes to be produced directly on the plotting instrument. Minor hand corrections may still be necessary. One of the prerequisites for such direct mapping is a high quality plotting table.

Computer-assisted direct mapping is also possible with an *analytical plotter*. The computer of such an instrument (Frontispiece) is even more efficient. The table is basically controlled by means of the computer. The operator's continual travel movements are resolved into small vectors which are then transmitted at a frequency of about 15 Hz as output to the table. The table must be capable of processing these small vectors transmitted in rapid succession. The movements of the measuring mark and plotting point should remain nearly synchronous, even if the table has to execute complex line types.

The more efficient computer can also handle more extensive application programs, e.g., the generation of contours from measured profiles, and can transmit these to the table

- at high quality as a fair drawing, or
- very quickly for checking purposes.

These off-line plots can also be produced parallel with measurements carried out on the instrument.

The analytical plotter also can have a large mass storage in which coded measurements can be stored, corrected, and then output to the plotting table. This is done off-line and very fast. The result is a control plot of what has been digitized. A control plot is generally also required while digitizing is being carried out. In this case, the table is run on-line, the operator determining the plotting speed. These control plots are typical for data acquisition and data checking in digital mapping. Thus, the plotting table connected to the analytical plotter has a multi-purpose function. It can be used either as a fast plotter or as a precision plotter. It is sometimes 'linked' directly to the operator (synchronous operation and delayed on-line operation) or is operated only by the computer (off-line operation).

Digital plotting tables are also required in *interactive graphic systems*. The data obtained from various sources, e.g., from a photogrammetric station, are combined, corrected, and are then plotted either very quickly for control purposes or at a high quality for fair drawings.

Performance Parameters

The performance parameters of a digital plotting table include:

- positioning accuracy
- line quality
- plotting time
- quality of supporting computer and software

The performance parameters are explained below on the basis of practical results obtained with the Aviotab TA2. This digital plotting table is described in detail by Höhle (1980).

Positioning Accuracy

When single points have to be plotted, the absolute positioning accuracy of the table is of prime interest. One method for routine checking of a plotting table is given below, where 1-m by 1-m grid plate of invar steel is used. Its 25 grid points are set by means of a microscope, and the table coordinates are directly transmitted to a computer. Three transformations to the required coordinates are carried out one after the other, having the following parameters:

Transformation 1:	translations in x and y and rotation.
Transformation 2:	as 1, plus scale.
Transformation 3:	as 1, plus rectangularity and affinity.

Further, the results of these transformations include the residual mean coordinate errors $m_{x,y}$ (rmse). The magnitude of these errors corresponds with the positioning accuracy as such. Still better results can be achieved by the computed correction of systematic table errors (scale, affinity, rectangularity). The same error values also apply for digitizing points that have already been plotted.

The mean values obtained with five standard serially produced TA2 tables using this method were as follows:

	Error Corrections Applied
$m_{x,y} = \pm 0.036$ mm	none
$m_{x,y} = \pm 0.024$ mm	scale
$m_{x,y} = \pm 0.015$ mm	scale, affinity, rectangularity

After taking into account all systematic errors, the residual mean coordinate errors were only $\pm 15\ \mu m$.

It should be noted that the plotting accuracy also depends on the behavior of the plotting medium (sheet) under changing conditions of temperature and relative humidity. Thus, for example, Duroscal scribing film will vary 0.05 mm per metre for every 10 percent change in relative humidity and 0.07 mm per metre for every 1°C temperature change. Precision plotting is thus possible only in rooms with stabilized climatic conditions.

The positioning procedure to individual points is carried out more or less statically. Plotting, on the other hand, is above all a dynamic process.

LINE QUALITY

Line quality is an important criterion for the quality of automatic plotting equipment. Irregularities in the straightness of a line or in line thickness can generally be recognized immediately with the naked eye. Irregularities may be specific to a given plotting tool and a given plotting material (sheet). Scribing is particularly critical. The following dynamic errors can occur in *straight lines:*

- waviness
- stepping
- start-up and braking errors
- tracking errors
- variations in line width

In the *transition from one line to another,* rounded corners may be produced. When plotting parallel straight lines in opposite directions, tracking errors may occur which will appear as variations in the space between the straight lines. Irregularities may also occur within the line itself, e.g., a blank at the start of the line, blanks within the line, and a collection of the coating material at the end of the line. When *circles and curves are plotted,* they need to be resolved into vectors. The vector size is computed by a built-in or external processor and may become visible. These various errors are briefly described below. The results obtained with the TA2 are also given.

WAVINESS

This term describes periodic oscillations about the nominal line. Waviness is due to the increment size and to mechanical oscillations and deformations.

The deviations, f (Figure 1.1), become more noticeable the shorter the wave length, p. They should be determined also for straight lines that are inclined only very little relative to the table axis.

The waviness of straight lines plotted with the TA2 has been determined for two serially manufactured instruments. The maximum value found was ±0.025 mm, while the mean value for ten points was ±0.017 mm. These straight lines were plotted at maximum speed.

A similar dynamic error is *stepping* (Figure 1.2). The size of the steps is determined by the drive system and the smallest increment. On the TA2, no stepping is discernible.

START-UP AND BRAKING ERRORS

When the plotting-head carriage is started up or braked, deviations from the straight line may occur (Figure 1.3). This error is produced by the difference in the inertia of the mass of the two carriages and by other factors. This error will be particularly apparent in short straight lines and in text or symbols.

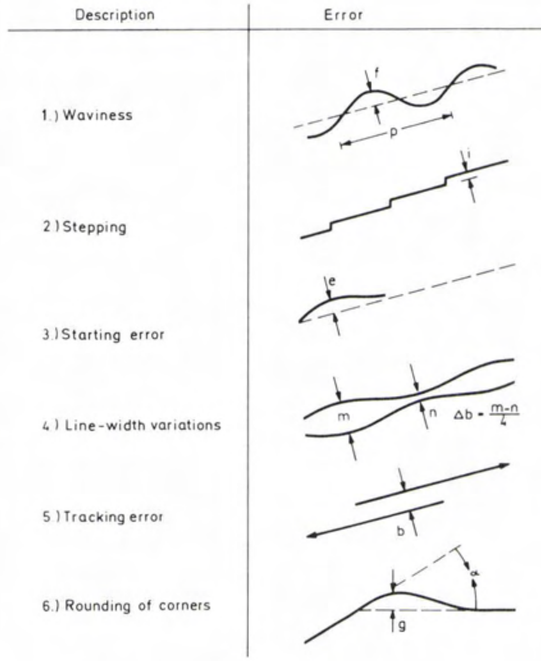

FIG. 1. Dynamic plotting errors.

Tests of two TA2 produced maximum errors of 0.045 mm, while the mean error at ten test points amounted to 0.030 mm. These errors can be reduced by halving the acceleration.

VARIATIONS IN LINE WIDTH

The width of a line may vary over its length (Figure 1.4). This may be caused by the scriber lifting off from time to time as a result of excessive plotting speed or by the state of the cutting edge or by its guidance in the direction of travel.

Using a 0.1-mm wide scribing needle for the TA2, variations at one edge of a line (Δb) occurred up to 0.012 mm. This fact should be taken into account when measuring other errors.

TRACKING ERRORS

If straight lines are plotted in opposite directions, tracking errors may occur. These errors are recognized as a variation in the distance between two parallel lines (Figure 1.5). In a test of serially produced instruments, maximum tracking errors $b/2 = 0.015$ mm were found.

ROUNDING OF CORNERS

If two straight lines are plotted after each other and if the change of direction is less than 45°, the speed of the TA2 at the end of the first vector is not braked to zero. This results in a higher plotting speed, particularly in the case of curves. However, as a result of the radial acceleration, oversteer occurs at the corners. In the TA2, the amount of rounding of corners is small.

CIRCLE DEFORMATION

Circles are represented by series of separate vectors. In the TA2, vectors can be generated in the table's internal control computer. The length and number of vectors varies according to the radius of the circle. If, for example, a circle having a diameter of 1 mm is plotted, it is represented by 13 vectors, each having a length of 0.2 mm.

PLOTTING TIME

The time taken to produce a plot determines the economics of a plotting table. In photogrammetry, plotting time is primarily determined by the maximum acceleration possible, and secondarily also by the possible maximum speed. In photogrammetric applications, a large number of short straight lines is usually present and maximum speed is therefore only rarely achieved.

The effect of acceleration on the average speed is shown in Figure 2. In plots consisting mainly of short vectors, the TA will take up to 3.5 times longer than the Aviotab TA2 with its greater acceleration. The maximum speeds of the two tables, however, are only in the ratio 1:2.4. These observations are based on traveling individual vectors in start/stop operation. The TA2 has a separate speed control. Thus, if the change of direction for the next vector remains below 45°, the traveling speed is braked only to a limited extent (Figures 3 and 4). With this speed control, particularly for plotting contours, for example, time gains can be obtained up to a factor of 2. At the same time, the line quality is better.

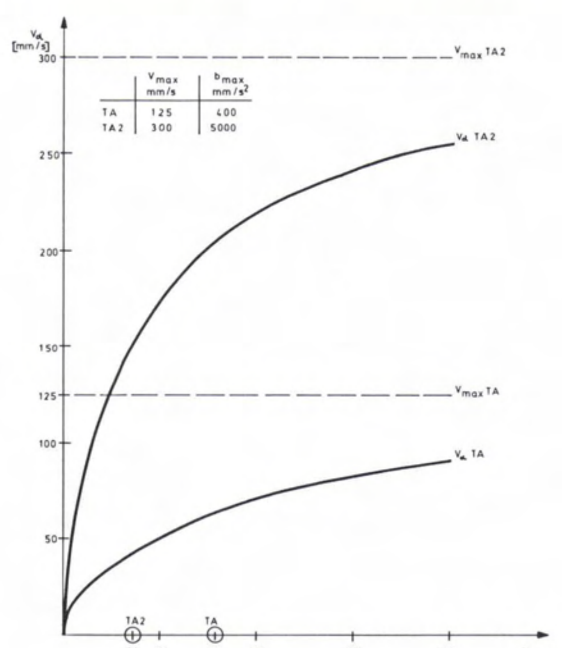

FIG. 2. Average speed, v_α, of TA and TA2 plotting tables as a function of the distance travelled, s. Each leg is run in start/stop operation. In the leg marked ○, maximum speed v_{max}, was reached before braking (b_{max} . . . max·acceleration).

PERFORMANCE PARAMETERS OF COMPUTER AND SOFTWARE

The digital plotting table is assisted by computer and software. A distinction is made between the internal control computer and the external computer. The data transfer from one computer to the other and the interfaces between them are also important components of the plotting system. These components will be investigated below with regard to their most important performance parameters. For a comparison of different plotting systems, the following need particularly to be examined:

- type and extent of functions
- speed and reliability of execution of functions
- possibilities for the table operator to intervene
- operator comfort.

INTERNAL CONTROL COMPUTER OF PLOTTING TABLE

In general, the control computer has the following tasks:

- controlling the table
- relieving the main computer
- digitizing set points

In order to carry out these tasks, the control computer possesses various programs which can be called up by software command or by hardware (switches, keys). In Table 1 the various functions of the TA2 control computer are listed. These various possibilities characterize the efficiency and capability of the table. The application determines their importance. By means of these software commands and hardware devices, the programmer and the operator can optimize plotting time and/or plotting quality. Some of the functions are started automatically. Thus, for example, it is possible to avoid braking to zero speed at the end of a vector if the change of direction of the following vector is previously established, and the speed is then reduced either not at all or only very little. Apart from this, the control computer can adapt to the characteristics of the plotting tool. The automatic tangential rotation of the scribing cutter, constant rotation of the tool, or the automatic feed of the pencil lead as it is used up are such special characteristics of the control computer which contribute to greater plotting quality and operator comfort. To simplify programming and *relieve the main computer,* it is most desirable that the control computer should be able to deal on its own with constantly recur-

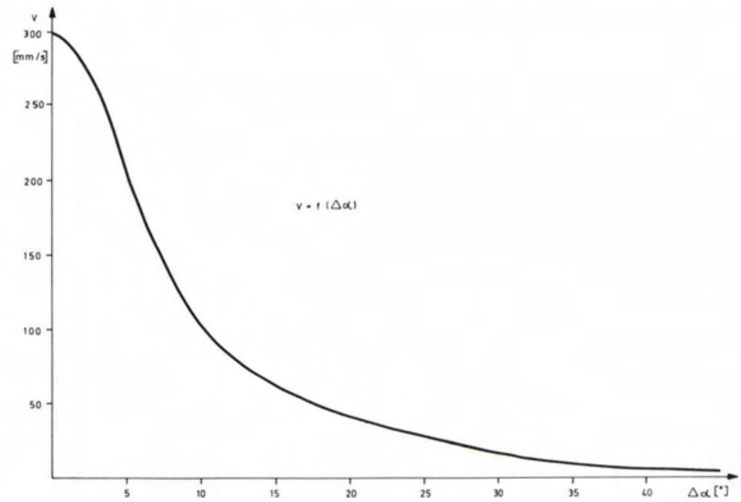

FIG. 3. TA2 speed control. Depending on the directional change relative to the previous vector, the maximum permissible speed, v, for the following vector is obtained from a table based on the graph shown.

ring plotting tasks. This applies particularly to the generation of vectors and circular arcs, including various line types. To optimize the speed, the programmer should be enabled to select the format (binary or decimal) and the absolute or relative coordinate reference point of the vector. To facilitate programming and relieve the computer, it is also desirable for text and symbols to be generated in the control computer. The performance parameters also include the *types of lettering* possible and other further possibilities of variation. Further, the elements available to represent them, e.g., straight lines, circular arcs, etc, and the resolution of the matrix are also of importance. In general, user requirements with regard to lettering are very diverse. The wide variety of requirements is not easy to satisfy by means of the table's internal control computer.

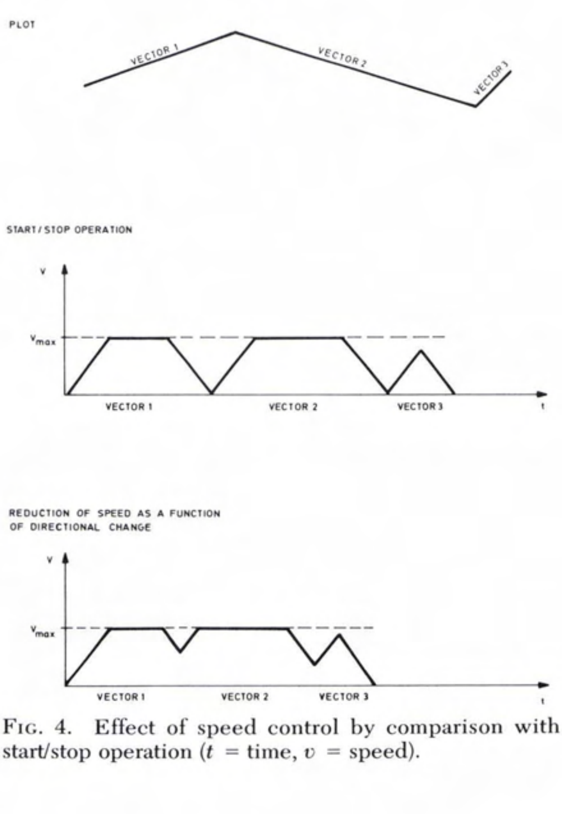

FIG. 4. Effect of speed control by comparison with start/stop operation (t = time, v = speed).

It is an important feature of a digital plotting table that it be able to *digitize the momentary position* by pushbutton or software command and to transmit this to the external computer. This digitizing capability makes it possible, for example, to orient the plotting sheet. In addition, it should be possible by means of software to establish the actual *state* of the table at any time, e.g., to determine activated switches, plotting point position, tool in use, etc. The possibility of obtaining such information is of particular importance if the plotting table is to be integrated in a system.

EXTERNAL COMPUTER

The plotting demands can be transmitted either on-line from a computer or off-line from magnetic tape. For on-line operation of a plotting table, the following considerations play an important part with regard to the computer:

- location and connection requirements
- computer category
- supporting plotting software

The suitability and performance of the table is, in

TABLE 1. CHARACTERISTICS AND PARAMETERS OF THE AVIOTAB TA2 CONTROL COMPUTER

Functions	Characteristics and parameters	
	Software	Hardware
Control of plotting-head carriage	—maximum speed (separate for pen-up and pen-down vectors) —automatic speed reduction (depending on directional change) —maximum acceleration —automatic reduction of acceleration (according to buffer content)	—maximum speed —maximum acceleration —automatic reduction of acceleration for tangentially controlled scribing tool
Control of plotting tool	—raising and lowering —time required for raising/lowering —constant rotation —tangential rotation —tangential rotation with change of direction —automatic pencil-lead feed —change-over of tool, two or four positions	
Generation of:		
Straight lines (vectors)	—five types of vectors • variable reference point (absolute, relative) • variable format (decimal, binary)	
Curves	—circle, circular arc	
Line patterns	—long-dashed line —short-dashed line —dot-dashed line —dotted line	
Lettering	—Three types of lettering standard ASCII character set • lower-case letters • special European characters • photogrammetric symbols • 5 × 8 matrix straight-line representation • variable height, angle and reference point	
Reliability of data transfer and plotting	—check of plotting commands for syntax errors —plot only within window defined by hardware —buffer for 512 bytes (25 vectors)	—stop immediately (manually by pressing a key or automatically with light barrier) —find absolute zero point for coordinates and reference point set for coordinates
Digitizing	—actual plotting point position —position of current reference point —coordinates of current plotting-area limits —status information on • plotting point raised/lowered • plotting point position 1–4 • manual/computer operation • actual speed/acceleration • tangentially controlled tool on/off	—release key
Functional checks	—display of error code	—test plot

TABLE 2. ADJUSTABLE INTERFACE-PARAMETER SETTINGS IN THE TA2

STOP bits	1	2
PARITY	ODD	EVEN
DATA bits	7	8
BAUD rate	110 . . . 9600	

part, also determined by the extent to which it can be adapted to different computers, as regards both hardware and software. The possibility of combining any given plotting table with computers is limited. The extent and quality of the plotting software is also an important determinant for the table's performance.

LOCATION AND CONNECTION REQUIREMENTS

To ensure perfect data transfer, the distance between computer and table needs to be within certain limits. Where the transfer speed is 9600 baud, the distance should not exceed 10 m. From the point of view of operating both the computer and the table, it is desirable for this distance to be reasonably short, with direct visual control.

The connection to the interface in the computer calls for the same interface in the table. The RS 232C interface is widely used. Despite agreed standards, there are nevertheless differences between one computer and another. The RS 232C interface in the table should therefore be capable of adjustment in a number of specific aspects (Table 2).

COMPUTER CATEGORY

Computers are divided into desktop computers, minicomputers, and main frame computers. For on-line operation of a plotting table, the output frequency of vectors is of primary interest. This should be adapted to the processing speed of the table.

The *output frequency* of plotting commands is a complex matter. It is determined by a number of factors, including:

- computer speed
- computations set by program
- access time to peripherals
- other tasks for which the computer may be required
- translation of programming language

The output frequency can be stated only for a given task and a specific computer configuration. In many cases, the computer automatically fills a so-called spooler memory on the disk, which in its turn automatically operates the plotting table. In the case of large computers, it is desirable to establish a plot file which can then be invoked at a second level for output by means of interface. This is carried out parallel with other programs in a multi-user system.

In the case of minicomputers such as the Nova 4/X, an independent plotting program can also be run in a background mode while the analytical plotter is controlled as a foreground task. From what has been stated, it will be seen that even with large computers it is possible for relatively slow output frequencies to occur. But this also applies to desktop computers in which the BASIC program needs to be constantly translated into machine language in order to execute the program. In such cases, plotting on the table becomes discontinuous. In the case of computers having a high output speed, where the table is slow, the table will no longer be able to keep up with the computer and the computer will be delayed.

In process control such as that utilized in computer-assisted direct plotting, the output frequency of the computer, the transfer speed of data via a cable, and the processing speed of the table's internal microcomputer need to be matched. This matching is a factor determining the performance capability of the complete system. These considerations particularly concern on-line operation. The operator's movements should be transferred synchronously to the table without producing intermittence or truncation. If the plotting process is not perfectly harmonious, this is immediately noticed and felt to be unsatisfactory.

SUPPORTING PLOTTING SOFTWARE

The software in the external main computer is generally written in a higher level programming language. There are different software categories (Figure 5).

Basic software contains a number of sub-programs for plotting tasks. These sub-programs make use of the commands given by the table's internal microcomputer. Subroutine names and variables conform often with those used by Calcomp. The basic software is integrated in the sys-

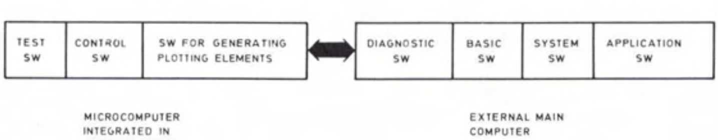

FIG. 5. Types of software for plotting tasks.

TABLE 3. TYPES OF PLOTTING SOFTWARE IN THE TWO PHOTOGRAMMETRIC PLOTTING SYSTEMS AVIOPLOT RAP AND AVIOLYT AC1

Plotting system / Plotting software	Avioplot RAP	Aviolyt AC1
Basic software	—Fortran IV for Aviotab TA and MP/100 micro-NOVA	—Fortran V for Aviotab TA2 and Nova 4/X
System software	—direct graphic mapping	—direct graphic mapping —digital mapping
Diagnostic software	—for checking table and operating keyboard	—for checking table and operating keyboard
Application software	—plotting of margin and control points —symbol derivation	—plotting of margin and control points —symbol derivation —computing and plotting contours

tem software and application software. This is available as a separate program package for programming by the user.

System software is necessary for the operation of a complete plotting system, e.g., computer-assisted direct plotting. This type of system may include not only the plotting table and computer but possibly also the photogrammetric measuring instrument and an operating keyboard. Measurement, computation, and plotting are carried out simultaneously. The operator can interrupt the sequence at any time and vary the parameters. Thus, programming is carried out interactively and this makes special demands on the software.

Diagnostic software checks the functional capability of the individual components of the system and identifies the cause of any failure.

Application software may be specific to the system and may use part of the system for the purpose. This type of program includes those used for plotting the margins of a map and for the derivation of symbols. Application software which is not specific to the system uses only the computer of the system.

An example is given in Table 3 for the different types of software used in the Avioplot RAP and Aviolyt AC1 plotting systems. Details of the software used in these systems are given by Höhle (1981) and Kreiling (1980).

Software quality is determined by a number of factors such as

- extent and type of functions; these must cope fully with all the user's task requirements.
- ease of operation; relatively unskilled staff should be able to use the software after a short period of familiarization; the software should prevent false manipulations
- the software should be continuously updated in the light of user experience.

REFERENCES

Höhle, J., *et al.*, 1980. Graphical output from the Wild Aviolyt AC1 analytical plotter by means of the new Wild Aviotab TA2 digital plotting table. Presented Paper to Commission II, 14th Congress of the International Society for Photogrammetry, Hamburg, 10p.

Höhle, J., and A. Jakob, 1981. New instrumentation for direct photogrammetric mapping, *Photogrammetric Engineering and Remote Sensing*, Vol. 47, No. 6, pp. 761-767.

Kreiling, W., and A. Hasler, 1980. The Wild Aviolyt AC1/Aviotab TA2: a computer-controlled photogrammetric system, Presented Paper to Commission II, 14th Congress of the International Society for Photogrammetry, Hamburg, 13p.

(Received 4 January 1982; accepted 30 June 1982; revised 29 August 1982)