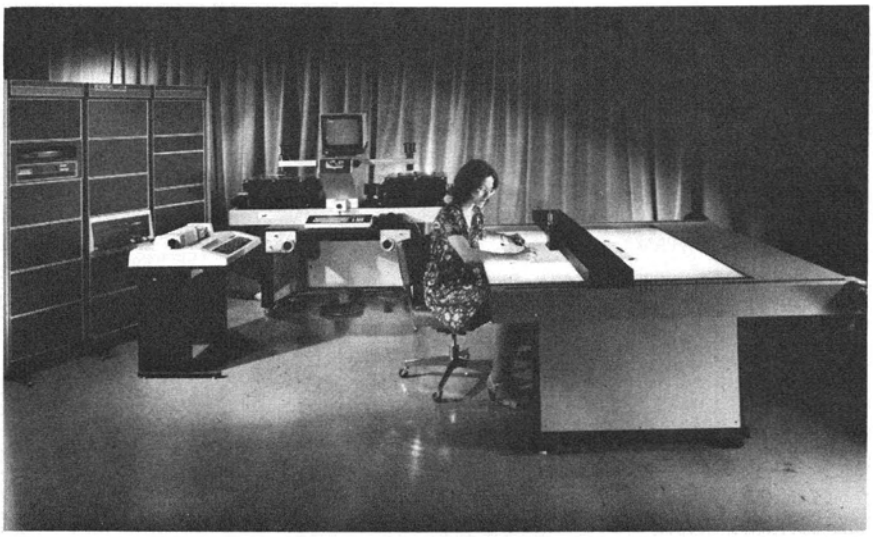

FRONTISPIECE. US-1 Universal Stereoplotter.

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The US-1 Universal Stereoplotter

The Bendix US-1 features versatility, flexibility, accuracy, and ease of computer programming.

(Abstract on next page)

INTRODUCTION

THE US-1 UNIVERSAL STEREOPLOTTER is a computer-controlled precision stereophotogrammetric instrument that uses the analytical reconstruction principle. First and foremost it is an analytical stereoplotter capable of performing any and all stereoplotting operations. However, equally important is the fact that the US-1 is a computer-controlled stereophotogrammetric instrument which is capable of being effectively and efficiently programmed to provide a wide range of operations other than those associated with stereoplotters.

Photogrammetry is entering an era where strong emphasis is being placed on the use of digital computers and analytical techniques. Indeed, the recent International Congress of Photogrammetry in Helsinki saw the introduction of a wide variety of new analytical stereoplotters. In the field, the US-1 stands at the top in providing precision, versatility, and adaptability. It is indeed much more than just a stereoplotter.

What makes the US-1 so outstanding? First, great attention was paid to all aspects of human engineering throughout the design process, both in the hardware and in the software. This resulted in an instrument which provides smooth, efficient operation. In addition, the 15 years of experience Bendix has had in the design and development of analytical stereoplotters and other computer-controlled stereophotogrammetric instruments resulted in a design that implements the analytical plotter principle to a greater extent than ever before. Finally, and most important, the software has been designed to be both versatile and flexible in order to provide a wide range of operations

PHOTOGRAMMETRIC ENGINEERING AND REMOTE SENSING,
Vol. 43, No. 11, November 1977, pp. 1399-1406.

while still making it possible for the user to develop and add new capabilities. Thus, he can structure the software to fit his particular operation.

As more and more emphasis is placed on digital techniques, the US-1 provides an excellent transitional tool from analog to digital. It is an adaptable, flexible instrument which can support and increase the efficiency of an entire photogrammetric organization. Because of its flexibility, it can provide the basis for the eventual integration of all the photogrammetric instruments in an operation. The reasons for this are that (1) it is a computer system providing strong computational capabilities; (2) it has software designed to provide the basic data flow and operational structure for general applications; and (3) it has been designed as a complete system with computer hardware, interface, and software carefully balanced to provide optimum operation. In short, it is everything that an analytical stereoplotter should be.

ABSTRACT: *The US-1 Universal Stereoplotter, designed and manufactured by Bendix Research Laboratories, is a precision stereophotogrammetric instrument that is controlled by a digital computer and uses the analytical reconstruction principle. It is intended for use in aerotriangulation, profiling, cross sectioning, large-and small-scale mapping, and digital data collection. The basic configuration consists of a stereoviewer, plotting table, control computer with associated peripherals, computer programs, control interface, and CRT terminal. Operator control is exercised through the CRT terminal which allows for the entry and display of various data items and furnishes an instructional sequence for the operator. Movement through the model is controlled by two handwheels and a footwheel.*

Operation of the US-1 is under control of a composite computer program, which in turn is composed of a set of program modes. The program is run under the computer's Disk Operating System (DOS), using standard software supplied by the computer manufacturer and making a maximum use of FORTRAN to simplify the addition to, or modification of, system programs. Thus, the operator may modify the delivered software system for his own special needs.

EQUIPMENT CONFIGURATION AND DESCRIPTION

The basic configuration of the US-1, shown in the Frontispiece, consists of a steroviewer, plotting table, control computer with associated peripherals, computer programs, control interface, and CRT terminal. A brief description of these major components is given below. Operator control is exercised primarily through the CRT terminal, the handwheels, the footwheel, various status switches, and two footswitches. Additional controls are provided for magnification and rotation control and base-in/base-out viewing.

STEREOVIEWER

The stereoviewer, shown in Figure 1, contains two precision *X-Y* measuring stages, a stereoviewing train, stage illuminators, and the major operator controls. It is suitable for use with color or black-and-white photography and accommodates film positives or glass plates up to 25 cm (10 inches) square.

The operator controls the system through the viewer handwheels and footwheel. These controls are designed for smooth response and sensitivity with both their sensitivity and direction controlled by the software. The *X*, *Y*, and *Z* control of the handwheels and footwheel may be easily interchanged or modified to control variable planes in the stereomodel.

The *x-y* stages provide precision positioning of the input photographs with respect to stationary optical viewer axes. The stages are driven by independent servo drives which consist of a DC servo motor mounted at one end and an incremental optical encoder mounted at the other end of a preloaded hard-mounted ball screw. The servo system has a precision of 0.001 mm with a maximum slewing speed in excess of 20 mm per second. Stage RMS error is no greater than 0.004 mm after computer-program removal of systematic error.

FIG. 1. US-1 stereoviewer.

The US-1 optical system contains a 6:1 mechanically compensated zoom lens for each axis, with a total magnification range from 5× to 30×. Both individual and common zoom controls are provided. In addition, each optical path is provided with a separate focus control. Focus is not affected by magnification variations with the Zoom. Neither is illumination intensity.

Controls are provided to rotate each image throughout a range of ±180° through the use of a dove prism. In addition, an optical switch is provided to interchange the images in the viewing eyepieces for base-in/base-out viewing.

The system has an interpupillary distance adjustment from 55 mm to 75 mm. In addition, squint adjustment is provided for both axes in the right eyepiece. The design permits the operator to wear eyeglasses.

The optical components which directly affect the precision of the instrument—the objective lens, reference mark, etc.—are mounted on a common plate which is attached to the lower (stationary) member of each stage. The zoom lens, dove prism, and optical switch are mounted on a base plate which slopes upward at a 35° angle in the center of the instrument in order to place the eyepieces at a convenient height for viewing. The eyepieces slope upward at a 15° angle.

PLOTTING TABLE

The plotting table, shown in Figure 2, is the graphic output device for the US-1 system. It is under computer control. It will reproduce, at a pre-selected scale of virtually any enlargement or reduction of model scale, any two of the three *X*, *Y*, and Z orthogonal dimensional movements of the floating mark within the stereoscopic model. The plotting table is back-illuminated, and has a working area of 1.1 by 1.4 meters (42 by 54

FIG. 2. US-1 plotting table.

inches). The height of the working surface is 30 inches above the floor.

The plotting table is driven by a DC servo system which provides a precision of 0.020 mm at a maximum slewing rate of 250 mm per second (10 inches per second). It provides a standard error of positioning any axis to sharply defined images of 0.2 mm. Under computer control, the plotting table can perform off-line plotting of stored digital data and delayed plotting with manuscript improvement features.

The carriage of the plotting table is equipped with a solenoid-driven Haag-Streit tool holder. This unit provides a highly accurate holder for standard scribe tools, pencils and pens, and alignment and pricking microscopes. Provision is made for adjusting stylus pressure.

Adjacent to the working area at each side is an open rectangular trough 4 by 4½ inches running the depth of the working area to hold excess working medium in roll form.

FIG. 3. US-1 digital controller.

DIGITAL CONTROLLER

The digital controller used in the US-1, shown in Figure 3, consists of a general-purpose digital computer with its associated peripherals and a specially designed control interface. The computer used in the US-1 is the PDP-11/35 general-purpose digital computer manufactured by Digital Equipment Corporation. It is equipped with 28,672 words of core memory, 1.2 million words of interchangeable disk memory, a high-speed paper tape reader/punch, and a teleprinter. It is used in the US-1 as a computational center and real-time control computer. Service for this computer is available worldwide.

A CRT terminal is provided with the system to allow the operator to enter and display data as well as to exercise control over the system. This device operates at a 4800 baud rate with absolute cursor addressing on a display screen providing 24 lines of 80 characters each. The US-1 system software utilizes the upper portion of the CRT display as a real-time display of operator-selected quantities such as ground, model, or photo coordinates.

The special-purpose digital interface controls the flow of information between the digital control computer and the viewer and plotting table. This includes transmission of position commands to the viewer stage and plotting table servo systems, transmission of position commands to the stylus, transmission of switch status from the viewer to the control computer, and accumulation and transmission of input commands from the handwheel and footwheel encoders.

The control interface uses replaceable MSI printed circuit cards with TTL logic. It is designed to provide smooth, rapid response to operator inputs. Use of PC cards provides high reliability and ease of service.

PERIPHERALS

In addition to the standard peripherals provided with the basic US-1 (magnetic disk, paper tape reader/punch, and teleprinter), it is possible to easily add a wide variety of other peripheral devices to configure the system as best suited to any particular operation. This includes such devices as magnetic tape units, cassette tape units, line printers, and card readers. All of these devices, and many more, are standard peripherals available directly from Digital Equipment Corporation. They can either be incorporated in the initial system or added later.

An especially convenient peripheral to add to a system is the magnetic tape unit, particularly if the system is to be used primarily for data collection or digital recording. The magnetic tape can be used as a backup to the disk as well as a primary data storage device.

SOFTWARE

The US-1 is a computer-controlled stereophotogrammetric instrument. As such, the better the software used to control the instrument the more versatile and practical are its operations. The power of the computer and the precision of the stereoviewer and

plotting table are amplified and brought to their full potential by the effectiveness and practicality of the software.

The US-1 programs are intended to provide the highest computational accuracy of any stereoplotter in the world, while providing the flexibility to allow modification by the user to meet his specific requirements.

PROGRAM STRUCTURE

Operation of the US-1 is under control of composite computer programs which in turn are composed of sets of program modes. These programs are run as overlay systems under the computer's Disk Operating System (DOS), which has control of calling stored programs and loading overlays as requested by the operator. Provision is made for the customer to add new program modes and modify standard modes for his own special needs.

The current US-1 system programs provide capabilities in three main areas:

- Normal stereoplotter operations,
- Optimized strip triangulation data gathering (bridging), and
- Strip triangulation adjustment.

These US-1 programs have been developed to provide maximum flexibility and modularity to simplify the task of developing user programs to perform special functions.

Provision is made in the US-1 software to model atmospheric refraction, Earth curvature, both radial and asymmetric lens distortion, and film deformation, as well as principal point offset and focal length. In addition, the programs enable the operator to input and display coordinate data directly in UTM or other grid-system ground coordinates, as well as stereomodel coordinates as is usually the case.

STANDARD PROGRAM MODULES

The standard US-1 software consists of a set of individual program modules which perform the various functions required for the proper operation of the system. These various modules provide for the following system operations:

(1) *Interior Orientation.* This module is used to establish the precise photo-to-stage coordinate transformation, i.e., the relationship between the stage coordinate system and the photo coordinate system. This also removes the effects of film deformation. With the US-1, the operator has a choice of several types of interior orientation computations, depending on the amount of data he has for the fiducial marks, all the way from a simple intersection up through a second-order polynomial fit. The stages are slewed rapidly to the approximate locations of fiducial marks, and stage motions are automatically engaged and disengaged to permit fast and convenient pointing.

(2) *Visit Points.* This module is used to observe and record coordinates for parallax points, pass points, and ground control points for use in the relative/absolute orientation computation. This module works in ground space and includes automatic slewing to specified points. It also allows the operator to move both photos simultaneously, based on existing orientation element values, and permits the operator to position one photo relative to the other to eliminate parallax. Normal handwheel operation is in the current ground (or model) coordinate system. However, through the use of status switches, it is possible to have the handwheels adjust the exposure station coordinates of one photo rather than ground coordinates. This effectively allows the operator to remove both x-and y-parallax.

(3) *Exterior Orientation.* This module is used to perform an automatic relative or combined relative/absolute (exterior) orientation. It uses the ground control point, pass point, and parallax point data gathered in the Visit Points module to calculate a least-squares solution for the orientation elements (exposure station coordinates and attitudes) for the two photos to form a stereomodel. The module will perform either a relative or an exterior orientation, based on the settings of data items by the operator. Any of the 12 orientation elements of the stereo pair can be held fixed during the solution, which is essentially a two-photo resection.

(4) *Table Preparation.* This module is used to perform an orientation of the plotting table coordinate system to the stereomodel ground coordinate system. It allows the operator to establish the relationship between the manuscript and the ground for plotting. Thus, if a previous manuscript is to be modified or updated, the exact relationship between the manuscript and the ground, including rotation and scale, can be established without cumbersome manual intervention by the operator. All that is required is that the X and Y ground coordinates of at least two identifiable points on the manuscript are known.

(5) *X-Y Plotting.* This module is used to plot planimetry, contours, or discrete points, operating directly in ground coordinates if desired. It allows the operator to move about the stereomodel in the active ground (or model) coordinate system and generate information either graphically (on the plotting table) or digitally (on the

magnetic disk or tape) or both. The program operates in either a continuous plotting submode or a delayed plotting submode. In the continuous plotting submode, the operator's movements through the stereomodel are plotted (graphically or digitally) with operator control of the stylus. In the delayed plotting submode, the operator can cause straight line plots, or the plotting of figures which consist of multiple connected straight lines. All the points to be connected are measured and then the output plot is produced which connects all the points with straight lines.

(6) *Profiling*. This module is used to perform terrain profiling with selected direction and spacing. It allows the operator to plot on the ground in the two dimensions of elevation and an azimuth through the model. Again, graphic or digital plotting or both can be performed. The azimuth through the model is selectable by the operator, as is the distance between profiles in the model and, independently, on the plotting table. Elevation exaggeration is possible.

(7) *Bridging*. This module is used to perform rapid strip triangulation data collection. It analytically ties together successive photographs along a strip by performing repeated relative orientation on successive models maintaining overall scale. The program is optimized for speed in performing a single photo interior orientation on the new photo, returning to the previous scale transfer points, moving to approximate locations of new scale transfer points, and relatively orienting the new photo to the old photo. In addition, the operator may measure and record points along the strip which are not used in the relative orientation computation but for which he desires adjusted strip coordinates (called auxiliary points). The program is designed so that work may be stopped at any point and resumed later without lost effort.

(8) *Playback*. This module is used to plot on the plotting table from stored digital data. It will provide a graphic output for the digital data recorded in either the *XY*-Plotting or Profiling modules.

Besides these standard program modules, the US-1 has a group of five independent off-line programs which perform a polynomial adjustment to strip coordinates with selectable terms. These computational programs are designed to provide complete strip adjustment of the strip data gathered in the bridging operation. These programs orient the entire strip to the ground. They also apply the results of the strip adjustment to all the data points collected (scale transfer points, parallax points, and auxiliary points). The adjustment is patterned after Schut (1966).

BREAK FUNCTIONS

During execution of the standard program modes, the operator can easily go from the normal sequence to a special group of functions. These functions, called break functions, operate at a priority level above normal mode communication and below normal mode viewer/table control. Thus, these functions interrupt the normal mode for a short time but do not affect normal servo system control. Upon completion of a break function, control is returned to the normal mode at the point it was interrupted.

These special functions are used to:

- Look at or change values of data items.
- Control the selection of data items to be displayed continuously on the CRT.
- Identify the data item to be affected by the incremental input controls.
- Set the origin point for the two- or three-axis direct-distance readout.
- Set the reference azimuth to which the azimuth display is to be referred.
- Prematurely exit a mode.
- Clear the CRT display.

All data items in the system—orientation elements, ground coordinates, lens distortion entries, etc.—are contained in a common data file. They are all operator-accessible at all times through the use of the break functions. Each data item is referred to by a unique two- to six-character label. In addition, some labels are shorthand for entire groups of data quantities, e.g., "EOELEM" means all 12 orientation elements. Labels are also used for procedural flags. For example, label "DIGPL" is used to control digital recording; 0 means no digital recording desired, 1 means digital recording desired.

The break functions each have a dedicated key on the CRT keyboard to initiate the function. These mode-independent functions provide the operator with a convenient and easy method for displaying and modifying data in the US-1.

OFF-LINE PROGRAMS

In addition to the composite programs, composed of the various modules described above, which control the normal viewer-plotter system operations, several supporting programs are included with the standard system or are currently under development. These programs are off-line programs written in FORTRAN, and are intended for use in pre- or post-processing US-1 coordinate

data or input parameters. These programs are described below.

(1) RADLEN. This program accepts a table of lens distortion amounts at various radii from the point of intersection of the lens axis and the film plane and calculates the radial distortion coefficients used by the US-1 programs. The radial lens distortion correction is applied in the US-1 equations as an odd-ordered polynomial of the form:

$$DR = K_1 r + K_2 r^3 + K_3 r^5$$

where K_1, K_2, and K_3 are the coefficients determined by RADLEN and r is the radius from the center of the lens.

(2) SKEW. This program is used to compute the stage scale and skew corrections for the US-1. The US-1 programs are designed to provide computer corrections to stage outputs to eliminate scale and skew errors. The SKEW program uses the results of an interior orientation on a calibrated grid plate to determine the scale and skew corrections for each stage. These values are then entered into data items for use by the US-1 programs.

(3) MODEL. This program is designed to use the results from the strip adjustment programs to compute the correct orientation elements for each stereomodel in a strip. The results of this program are a series of data files, one for each model, which can be used to reset those models on the US-1 without the need to perform an absolute orientation. All the data necessary to reset the model will be computed off-line.

Applications

No description of the US-1 would be complete without at least a few words about the applications for which it can be used. As an analytical stereoplotter, many of its applications are quite obvious. However, even with these, there are significant advantages associated with the US-1 over traditional stereoplotters.

It is possible to use photographs made from virtually any camera with the US-1. Since the model orientation parameters are maintained mathematically, there are essentially no limits on the computational ranges available. Also, it is possible to use two photos from dissimilar cameras to form the stereomodel.

An additional advantage with the analytical stereoplotter is the fact that it can accept digital model orientation data for direct model setup without requiring the operator to perform a relative/absolute orientation. This can provide a very significant time and cost savings for those operations which do any resetting of previous models, e.g., for map updating, remeasurement of points, addition of map detail. In addition, this alleviates the model reset problem where an operator cannot finish with the model in his shift. It is not necessary to leave the model on this instrument (thereby tying up the instrument) or to redo the relative/absolute orientation (time-consuming). This can streamline the efficiency of any photogrammetric operation.

Perhaps the most efficient and cost-effective use for the US-1 at this time is in strip triangulation. The US-1 has a software package developed to optimize the speed and efficiency of the strip triangulation data collection process. Not only does the computer take care of the data flow and operation sequencing, it can eliminate the need to mark scale transfer points and make redundant measurements. Orientation and tying of models happen analytically according to the method of least-squares. This process can identify faulty measurements during the actual data gathering process, not during the adjustment process which requires the model be reset to remeasure the point. In addition, the computer remembers the location of scale transfer points from one photo to the next. Thus, it is unnecessary to mark these points prior to bridging. The computer automatically returns to the point on the old photo that is to be transferred to the new photo in the strip.

Not only is the time required to preprocess the photographs saved, the typical instrument time required per model on the US-1 for bridging is less than 15 minutes.

Provided as a companion to the bridging program is a series of five programs which provide a complete strip adjustment capability. These programs use the data gathered in bridging directly to adjust the entire strip to the ground.

This last item highlights another strong point of the US-1. The system uses a general-purpose digital computer as a computational center. This computer is available to perform other off-line operations such as strip adjustment. Thus, not only does the user acquire an accurate, efficient photogrammetric instrument, but also a stand-alone computational center which is extremely powerful. As an example of the versatility of this computer, we have developed a program which provides an image display and point measurement capability for LANDSAT digital image tapes.

These areas discussed above are by no

means the only effective applications for the US-1. They do represent the areas where we have developed standard software modules for the US-1. However, it is most important to keep in mind that the US-1 software has been designed and developed as an extremely flexible and modular system to facilitate the addition or modification of modules to meet specific user needs. Certainly, various engineering applications such as highway construction, engineering measurements, and urban mapping can effectively utilize the power of the US-1, as can non-cartographic areas. In addition, the instrument can be effectively utilized as a stereocomparator with all the advantages associated with computer-controlled stereocomparators. The applications for this instrument are seemingly unlimited and have just begun to be exploited.

SUMMARY

The introduction of digital control techniques into commercial photogrammetric instruments is just beginning. It will continue at a rapid pace as all the advantages are realized. The US-1 is certainly a leader in this new wave. The US-1 is designed to give the highest stereoplotting accuracy of any present production stereoplotter while at the same time providing the utmost flexibility in the photogrammetric parameters.

Not only has software been developed to provide the US-1 with all the operations needed for normal mapping applications and strip triangulation capabilities, but it has been designed as modular FORTRAN programs with the goal of maximum flexibility.

The US-1 is truly a universal stereoplotter, or rather, a universal computer-controlled stereo-photogrammetric instrument; a "stereoplotter plus."

REFERENCE

Schut, G. H. *An Introduction to Analytical Strip Triangulation with a Fortran Program*, Publication AP-PR34 of the Division of Applied Physics of the National Research Council of Canada (NRC-9396), December 1966.

Annual Meeting

American Association for the Advancement of Science

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12-17 February 1978

Topics to be covered at the Meeting, to be held at the Sheraton-Park Hotel, include: sociobiology; advances in knowledge using recombinant DNA techniques; space exploration and the search for extraterrestrial intelligence; recent extremes in weather and long-term climatic patterns; stress; aging; the high school class of 1972; nuclear and alternative energy systems; whistle-blowing and scientific responsibility; desertification; minorities, women, and the handicapped in science; and over a hundred others. Further information about the meeting is available from the

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