FIG. 1. AS-11B-X system.

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A Digital Elevation Data Collection System

The AS-11B-X automated stereomapper employs laser scanning along epipolar lines and digital correlation to extract elevation data.

(Abstract on next page)

INTRODUCTION

THE AS-11B-X AUTOMATED STEREOMAPPER, shown in Figure 1, is an experimental instrument for rapidly and accurately extracting topographic data from stereo aerial photography of frame and panoramic camera systems. Unlike most stereoplotter systems which are designed primarily for generating analog information in the form of contours, profiles, and planimetry, the AS-11B-X was designed specifically to generate elevation data in digital form, and to do this efficiently at very high rates and accuracy. The experimental system includes an AS-11B-1 viewer and control computer, because this represented the quickest and most cost-effective way to provide a demonstrable model. Thus, the experimental model also will permit operations similar to the AS-11B-1. AS-11B-X techniques include use of a precision laser scanner for epipolar scanning, analog-to-digital conversion of photo data, digital storage, digital correlation, and generation of multiple profiles of elevation data in a single pass.[1,2] The elevation data are generated in real-time in an epipolar coordinate

ABSTRACT: *Most stereoplotter systems currently in use were designed primarily for producing contouring and profiling outputs on a coordinatograph. Recently, however, there has been an increasing need for topographic information in the form of digital grid-point elevation data. Whereas some existing systems can be used to extract this type of data, they cannot do it rapidly or efficiently. The AS-11B-X system is an experimental model of a new type of system intended explicitly for the collection of digital elevation data. The system was developed for Rome Air Development Center by Bendix Research Laboratories. The system achieves an increase in data collection rates of from 10-50 times that presently being obtained with conventional systems at no decrease in accuracy. The AS-11B-X system obtains its high data-collection rates by processing multiple lines of elevation points in parallel using digital processing. A combination of special techniques is used to simplify the digital processing and to reduce the amount of data storage required.*

system. In an off-line mode the elevation points are interpolated to a fixed grid; this may be accomplished on the AS-11B-X control computer or on an off-line computer.

AS-11B-X CONCEPT

The AS-11B-X concept uses the following combination of techniques:

- Single scan of each resolution element
- Digital image storage and address modification
- Epipolar scan
- Scan across multiple profiles
- Mechanical scan of laser light spot
- Multiple-bit digital correlation
- Elevation computation in epipolar coordinate system
- Off-line computation of fixed grid of elevation points

The following subsections discuss the use of these techniques.

SINGLE SCAN OF EACH RESOLUTION ELEMENT

The density at each resolution element of each photograph is scanned and measured only once for correlation operations. This is in contrast to scanning a resolution element each time its value is needed to perform a correlation operation. The system ability to operate with a single measurement of each resolution element depends upon digital image storage and accessing through address modification. Once a resolution element is measured, its density value is stored (digitally) and accessed as needed for correlation operations.

Measuring each image element only once increases the system speed potential compared to that of the AS-11B-1. Single scanning reduces the number of measurements needed to completely process an image area; for a given measurement speed, this increases the image area which can be measured per unit time. As with any measurement operation, measuring image element density is limited in speed (for any given accuracy and technology).

It must be noted that scanning several times for correlation operations is different from scanning several times for averaging to reduce noise. In the AS-11B-1, each resolution element is scanned several times and the results are averaged (after correlation) to reduce noise effects. This process of multiple scanning and averaging is repeated 3 to 30 times for different correlation operations. The AS-11B-X approach requires measuring each resolution element only once for correlation operations. In this approach, measurement could be done by scanning each image element several times and averaging (density) to obtain the single measurement; however, in the AS-11B-X implementation, each image element is scanned only once in a way which does not require repetitive scanning and averaging to reduce noise.

DIGITAL IMAGE STORAGE AND ADDRESS MODIFICATION

After a resolution element is measured, its density value is digitized and stored in a random-access memory from which it is read as needed for correlations. For correlation operations requiring different shaping of image data (in the sense of scan shaping), density data are read from the memory in different orders as required to obtain the desired scan shaping effects; this is done by appropriately modifying memory addresses for data retrieval. Fortunately, it is necessary to store each resolution element density for a limited time only. The value must be stored only until the immediately surrounding area has been scanned; all correlation operations can then be completed and density value can be discarded.

Shaping image data by address modification during storage or retrieval of data from memory reduces scan shaping requirements upon the scanner mechanism and permits use of the mechanical deflection scanner discussed subsequently. In concept, the image could be scanned in any pattern having the necessary resolution; in practice, the image is scanned in a uniform manner, but the scanning is somewhat shaped in order to reduce the data storage and retrieval problems. This topic is discussed next.

EPIPOLAR SCAN

Image density is scanned and measured on each photograph along corresponding epipolar lines. That is, each image is scanned along the lines where an epipolar plane intersects each photograph. An epipolar plane is any plane passing through the perspective centers of the two photographs of a stereopair, as shown in Figure 2.

Scanning along corresponding epipolar lines greatly reduces the difficulties of image data storage and image data shaping by address modification, because determining terrain elevation requires only correlation between image elements along these epipolar lines. The uncertainty in terrain elevation is reflected only in uncertainty in the location of corresponding image elements along the corresponding epipolar lines. This is in contrast to all other scan patterns, where uncertainty in elevation produces uncertainty in the location of corresponding image elements in both scan dimensions. Of course, the residual y-parallax in the stereomodel produces uncertainty in both scan dimensions, but this uncertainty is always small.

Epipolar scan lines are essentially straight lines over substantial distances on each photograph, thus allowing simple straight-line scanning. An epipolar plane cuts any frame photograph in a perfectly straight line, in the absence of non-idealities. An epipolar plane intersects each panoramic photograph in a slightly curved line (unless the photography is perfectly vertical, in which case it intersects in a straight line). However, the amount of this curvature is only a few micrometers across the entire photograph, for all expected panoramic photography characteristics. Furthermore, the curvature on the two panoramic photographs is very similar, thus causing straight-line scans to scan very nearly corresponding imagery, although not strictly epipolar lines.

Photograph non-ideality produces curvature of epipolar lines for both frame and

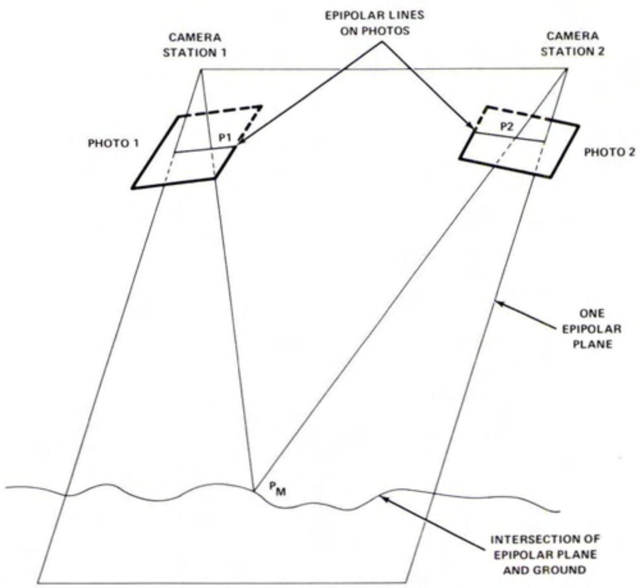


FIG. 2. Epipolar scan lines.

panoramic photography; however, the amount of this curvature is sufficiently small to permit straight line scanning over substantial distances. Over somewhat larger distances, the curvature produces uncertainty in the location of corresponding image elements, due to elevation uncertainty, between only a few adjacent scan lines.

SCAN ACROSS MULTIPLE PROFILES

Photographs are scanned along epipolar paths across many profile lines parallel to the direction of mechanical carriage motion, to obtain information on many parallel profiles or parallel lines of grid points. The image density information obtained in the region of each profile is to all intents and purposes processed separately to obtain independent measures of elevation for each profile.

Parallel measurement of parallel profiles permits measurement to proceed at many times the rate of mechanical motion of the optical-mechanical elements, including their servos. It thus avoids the technical and cost limitations of high-speed mechanical motion.

Figure 3 illustrates the way in which many profiles are processed at once. A total of 1280 data points are collected along a swath by scanning along successive epipolar lines across the swath. The 1280 data points are sampled along the epipolar lines at a spacing of 20 micrometers. The epipolar lines are spaced 50 micrometers apart. Each scan line is divided into many segments (profiles). A separate parallax value is determined for each segment along the scan line. Elevations determined for corresponding segments on successive scan lines generate profiles. As many profiles as there are segments can therefore be generated at once; the AS-11B-X will generate 58.

MECHANICAL SCAN OF LASER LIGHT SPOT

Image scanning is performed by mechanically deflecting a laser light across the photograph. The photograph stage is mechanically moved with respect to the scanner to scan in the other direction.

In CRT (cathode-ray-tube) scanning, the brightness of the spot is limited by the CRT phosphor; with dense photography, this brightness produces only a small amount of transmitted light. The small amount of transmitted light produces a low signal and thus a low signal-to-noise ratio. Mechanical scan deflection permits a very bright light spot to be used, which provides a higher scanner output signal-to-noise ratio. The signal-to-noise ratio is higher at the same scanning speed, and/or the same signal-to-noise ratio can be obtained at a higher scanning speed. The spot brightness is limited only by the detector or by heating of the film.

MULTIPLE-BIT DIGITAL CORRELATION

Correlation of imagery from the two photographs is performed digitally by multiple-bit multiplication of corresponding image element densities. The image element density products are added over desired image areas, producing data integration over these areas. In the AS-11B-X, the digital correlation, together with address modification for data shaping, is performed on-line by special-purpose digital logic to obtain the required speed. This is in contrast

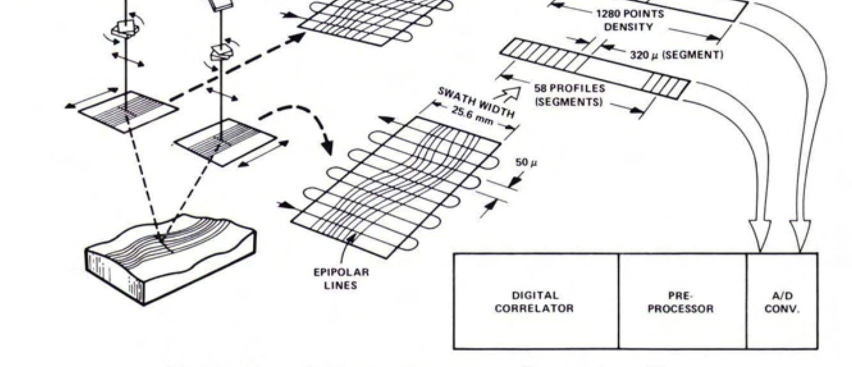


FIG. 3. Simultaneous processing of several profiles.

to the methods used in the AS-11B-1. It provides a convenient way to handle many parallel profiles at once without an excessive amount of hardware. It also allows a more ideal calculation of correlation to be made. Since all processing is digital, it is practical to use minicomputers to assist in the calculations. This permits a considerable measure of flexibility in the correlation process. The disadvantage of correlating digitally is that the hardware is more complex than the hardware used in the AS-11B-1 system. The digital correlator has a digital semiconductor buffer memory for density value storage, special-purpose digital logic for address modification and basic correlation operations, and two mini-computers for correlator control and data manipulation. The digital correlator also includes a monitor scope for checking system operation. The minicomputer programs are written in microprogram language to achieve higher processing speed and efficiency.

Figure 4 indicates the equation used for calculation of normalized correlation and illustrates the organization of a hardware parallel processor which can be used to calculate correlation. Covariance can be used instead of normalized correlation to determine the best image match between the two photographs. This is desirable since covariance is easier to compute. Covariance is the numerator of the expression for correlation. Complete normalized correlation is used only for evaluation of system performance and determination of system strategies.

The purpose of the digital correlator is to measure the amount of shift or parallax between correponding segments of imagery on two stereo photographs. This is done by computing correlation for several shift positions to either side of the expected shift position. The shift at which maximum correlation (or covariance) is obtained is the position of best image match and a measure of parallax between the two photos.

ELEVATION COMPUTATION IN EPIPOLAR COORDINATE SYSTEM

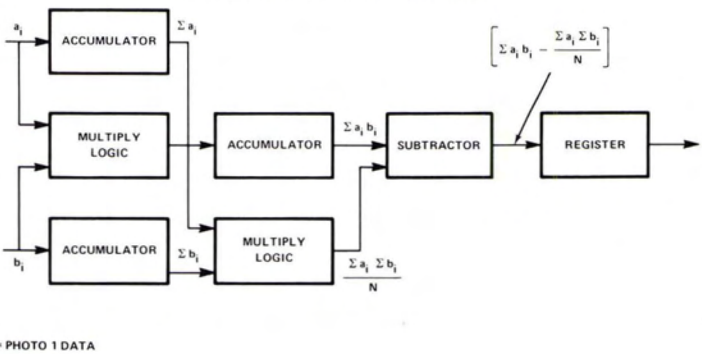
Final computation of the desired elevation values also is performed on-line. Thus, the operations performed on-line are those necessary to maintain scanning of corresponding epipolar lines on the two photographs, the correlation operations necessary to determine parallaxes along the epipolar line, and the computations necessary to convert the parallaxes into the corresponding model coordinates.

OFF-LINE COMPUTATION OF FIXED GRID OF ELEVATION POINTS

The final computation of elevation points in a matrix format is accomplished off-line. The off-line computations convert the elevation points from the epipolar coordinate system, by an interpolation scheme, into a fixed grid or matrix at a spacing determined by the user.

$$\text{CORRELATION} = \frac{\left[\sum_i^N a_i b_i - \frac{1}{N}\sum_i^N a_i \sum_i^N b_i\right]^2}{\left[\sum_i^N a_k^2 - \frac{(\Sigma a_k)^2}{N}\right]\left[\sum_i^N b_k^2 - \frac{(\Sigma b_k)^2}{N}\right]}$$

PARALLEL PROCESSOR FOR DIGITAL CORRELATION



a_i = PHOTO 1 DATA
b_i = PHOTO 2 DATA
i = POINT NUMBER
N = NUMBER OF POINTS BEING CORRELATED

FIG. 4. Digital correlation.

FILL-IN CAPABILITY

As with the AS-11B-1, the AS-11B-X includes a fill-in mode of operation. This consists of recording the beginning and end points of sections of a plot line wherein the correlation value is below an established threshold, thus making the data unacceptable. This condition can be due to lack of detail in the imagery, extremely dense imagery, and severe changes in slope of the terrain. Upon completion of the model in the automatic mode the operator then initiates a fill-in mode. The beginning point of each gap is recovered by the computer driving to the appropriate model point; the operator then uses the handwheels and footwheel to manually plot through the bad area, recording the new data on magnetic tape.

AS-11B-X Implementation

The AS-11B-X system employs the basic system organization shown in Figure 5. The major elements of the system are—

- Viewer/Scanner
- Control Computer
- Digital Correlator
- Magnetic Tape Unit
- Coordinatograph

The viewer/scanner unit has stages to hold a pair of stereo photographs, and a laser scanner and detectors to extract image density data from the photographs. The control computer controls photo carriage position and scanner operation so that the corresponding epipolar lines are scanned on each photograph. The image density data are supplied to the digital correlator, which separately correlates image data from many regions of the photographs to determine parallaxes.

The parallaxes are sent to the control computer where they are converted to model elevations and outputted on magnetic tape. The recorded elevations are not in final form, however, since they correspond to an irregular grid. The magnetic tape is subsequently read back into the control computer, which does the off-line processing to determine elevations for the desired grid. The control computer also uses stereo-model orientation and correlation data in determining grid elevations.

VIEWER/SCANNER

The viewer/scanner consists of an AS-11B-1 type viewer with an epipolar laser scanner system replacing the CRT scanner. It includes photo carriages, servo motors, laser light source, photo scanners, scan rotation optics, photo-diode detectors, and viewer optics. The operator's panel at the viewer unit contains the controls used for manual and automatic operation of the system. The control panel also contains a display for numerical data.

CONTROL COMPUTER

The control computer is basically an AS-

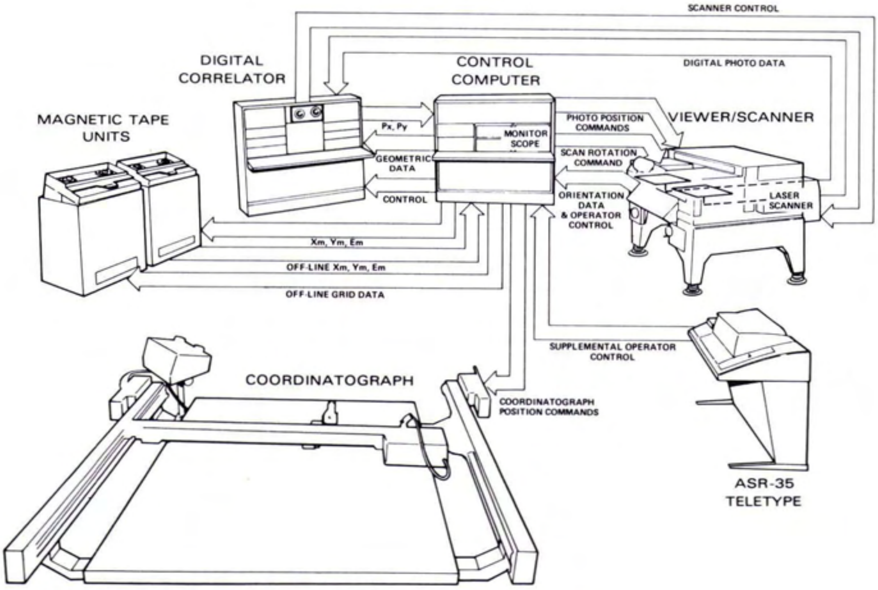


FIG. 5. AS-11B-X system organization.

11B-1 type digital computer system used for supervisory control and control of the epipolar scanning process. The control computer has a 16K memory, a 300-character-per-second paper-tape reader, a 50-character-per-second paper-tape punch, and a Model ASR 35 teletype unit as standard peripheral equipment. The motions of the photo carriages are controlled with servo motors. The servo motor inputs are obtained from digital-to-analog converters connected on the control computer I/O bus. A DMA (Direct Memory Access) channel is provided for communication with the magnetic tape units. The control computer programs used are modified AS-11B-1 system programs.

DIGITAL CORRELATOR

The digital correlator consists of analog-digital converters, a buffer memory, address modification logic, a parallel processor, and two minicomputers. The various parts of the digital correlator are described briefly in the following paragraphs.

Analog-Digital Converters. The analog-digital converters are high speed 8-bit converters which convert scanner outputs to digital image data.

Buffer Memory. The buffer memory is a high-speed random-access semiconductor memory which provides temporary storage for four scan lines of image data. It provides rapid access of image data by the parallel processor during the time that correlation is being computed.

Address Modification Logic. Address modification is performed by special-purpose hardware. It is required to correct for photographic and scanner distortion and for parallax between conjugate photographs. Geometric and scanner address modification is implemented by altering the locations along the scan line from which data are collected. Parallax address modification is performed by altering the location from which data are read from the preprocessor minicomputer memory.

Preprocessor Minicomputer. The preprocessor minicomputer is a Micro 1600 minicomputer. It is used to collect data from the analog-digital converters, provide temporary buffer storage, and compute table entries for the geometric address modification hardware. The preprocessor minicomputer supplies data to the buffer memory.

Correlation Minicomputer. The correlation minicomputer is also a Micro 1600 minicomputer. This minicomputer is used to collect correlation data from the parallel processor and to perform computations needed to supply the control computer with parallax data. The correlation process is controlled by this minicomputer.

Parallel Processor. The parallel processor is a special-purpose digital processor design to rapidly perform correlation computations. The parallel processor obtains image data from two photos and determines parallax by correlation measurements on selected line segments from each photo. The parallel processor computes the sums, products, and sums-of-products required to measure normalized cross-correlation between conjugate points on the two photos. The parallel processor contains high-speed parallel multipliers, arithmetic logic, registers, and counters.

MAGNETIC TAPE INPUT-OUTPUT

The magnetic tape input-output is provided by two Ampex TM-7 tape units which are interfaced to the control computer. These units are 7-track IBM-compatible. They have a recording speed of 45 inches-per-second and a selectable packing density of 556 or 800 bits-per-inch.

COORDINATOGRAPH

The coordinatograph provides a capability to generate contours and profiles manually in addition to providing an on-line monitoring capability. This hardware capability has been provided for the experimental model; it will most likely not be included in follow-on systems.

OFF-LINE COMPUTER

In the AS-11B-X system, the control computer is used for off-line computations when not being used for epipolar scanner control. This is done to eliminate the need for a separate off-line computing facility in this experimental model. The control computer is provided with two magnetic tape units so that digital correlator output data can be read in on one unit and processed data can be recorded on the other unit.

AS-11B-X Experimental Results

Final acceptance tests have been conducted on the AS-11B-X by the Defense Mapping Agency Aerospace Center (DMAAC). The results indicate data collection speeds well in excess of those obtainable on an AS-11B-1 with no decrease in accuracy. Digital data have been collected at rates in excess of 200 points-per-second. At this rate, data collection for a typical model can be completed in about ten minutes.

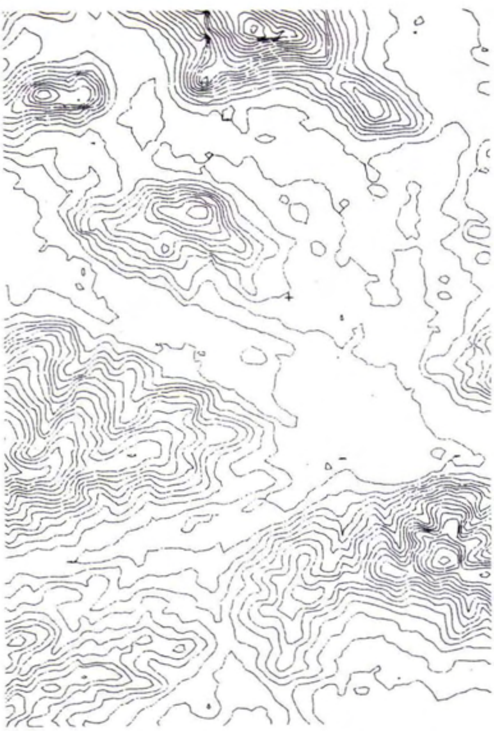


FIG. 6. Ft. Sill contours compiled from AS-11B-X digital data.

Three to four hours would be required to collect the same amount of data using an AS-11B-1.

An example of the data collection capability of the AS-11B-X is illustrated in Figure 6. It shows a portion of a contour map prepared by DMAAC from elevation data collected on the AS-11B-X. The contours match reasonably well with contours measured by other means although no absolute orientation was made. The data for the entire map, which was more than three times larger than the portion shown, were collected in a time of nine minutes. Additional time was required for off-line processing and plotting, however.

FOLLOW-ON

The AS-11B-X system will serve as an experimental test bed for a production prototype of Advanced Compilation Equipment (ACE). Though the basic concepts of the AS-11B-X will be embodied in the ACE, the configuration in terms of hardware will most likely be different. A design study being undertaken by Bendix for RADC and DMA to provide this design data is currently in progress.

ACKNOWLEDGMENT

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