*The PRA TSS (Terrain Scanning System) for Electronic Photogrammetry**

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ABSTRACT: *The preliminary design of the TSS, an automatic system of map compilation using no photography, is described. Terrain information is obtained by scanning the ground photoelectrically along a longitudinal line and two transverse lines simultaneously. The resulting electrical signals are stored on magnetic tape in the aircraft. At the conclusion of the flight, the tape is rerun and the signals are automatically oriented, scaled, corrected for relief, and adjusted to control by electronic means. The signals are then used to print a corrected photomap, carve a relief model, or produce a map manuscript.*

INTRODUCTION

AUTOMATION of map compilation is a logical result of modern advances in electronics. Several approaches to automatic map compilation and electronic photogrammetry have been described previously,[1] including automatic electronic ground scanning systems.

The *PRA TSS* (terrain scanning system) is a system for acquiring all necessary terrain information by scanning the ground photoelectrically, and automatically producing a corrected orthographic photomap. No photographic processes are used to acquire the terrain information. The varying light intensities received by the airborne scanning components of the *TSS* are converted to electrical video signals by photomultiplier tubes; these signals are immediately stored upon magnetic tape in the aircraft. The magnetic tape takes the place of the photographic film in conventional mapping. The procedures equivalent to orientation, scale adjustment, and relief measurement are carried out electronically in the *TSS* by automatically matching and modifying the electrical waveforms produced when the tape is read out. The proposed system is designed to print a fully corrected photomap and carve a relief model automatically. The *TSS* can also produce a corrected map manuscript with the aid of a photo interpreter.

A preliminary design study of the *TSS* has been made and the results are presented in this paper. The major potential advantages of the system, as presently conceived, are:

1. The mapping operation can be carried out with the characteristic high speed of electronic computers.
2. The system is completely automatic except for photo interpretation. Therefore fewer technically trained personnel are required to map with the *TSS* than with conventional compilation methods.
3. Under certain conditions, the *TSS* can operate at lower levels of ground illumination than conventional aerial photography.
4. Photographic processes are dispensed with. The *TSS* is not affected by radioactive dust in the atmosphere.
5. Size and weight of the airborne components of the *TSS*, including the magnetic tape, are practical for installation in aircraft.

Several major difficulties of the *TSS* re-

[1] Rosenberg, Paul, "Information Theory and Electronic Photogrammetry," PHOTOGRAMMETRIC ENGINEERING, Vol. XXI, No. 4, Sept. 1955, pp. 543–555.

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quire further study. These include high stabilization of the airborne scanner and complexity of some of the electronic circuitry.

Description of the System

The components of the *TSS* are described and discussed below in the approximate sequence in which they handle the flow of terrain information, as shown in the block diagram of Figure 1.

The light from a small spot on the ground is collected on the cathode of a photomultiplier tube through a telescopic lens of restricted field. (See Figure 2.) The photomultiplier tube gives an electrical output signal proportional to the total light intensity received from the spot on the ground at any instant. The telescopic lens serves as a light collector rather than an image-forming device. The light comes to the telescopic lens by reflection from a rotating mirror or prism; hence the spot being viewed moves along the ground in a path called a scan. Other laboratories (e.g. Haller, Raymond & Brown, Inc., and Boston University Optical Research Laboratory) have previously demonstrated the feasibility of gathering ground information by photomultiplier scans of this type.

The *TSS* incorporates a set of three simultaneous, continually recurring scans, as shown in Figure 3. One scan covers a line in the *Y* direction perpendicular to the heading and forward of the aircraft. A second scan views a similar line in the *Y* direction subtending the same stereo angle behind the aircraft. A third scan proceeds along the line of heading perpendicular to the other two scans. The two transverse scans (*Y* direction) provide detailed stereo coverage of the terrain. The longitudinal scan (*X* direction) is used for ground track recording only. All three scans not only cover the area to be mapped but extend to and beyond the horizon in each direction. The horizon signals are an aid in rectifying the transverse scans.

As the aircraft moves along the flight line, the transverse scans advance correspondingly. The spacing between adjacent transverse scans is chosen equal to the width of the scans, so that neither underlap nor overlap occurs. The transverse scans are designed to cover the mapped ground area with uniform angular speed and the desired resolution; however, beyond the edges of the flight strip, resolution can be sacrificed and the speed of the scanning spot can be increased as the scans extend to the horizon. A variable speed scan of this sort is obtained by suitably curving the reflecting surfaces of the rotating prism or mirror.

The output of the photomultiplier is a time-varying voltage containing a range of video frequencies. The voltage signals from each of the three scans are stored on magnetic tape within the aircraft; hence the magnetic tape is analogous to the photographic film of conventional aerial photography. However the arrangement of information in the two storage devices is different. On the photographic negative the ground image retains its identity as a two-dimensional area display of information. On the magnetic tape the information is stored in a one-dimensional form. Since an area display of information is not available in the magnetic tape, optical projection methods of compilation are no longer appropriate. On the other hand, electronic circuitry is particularly well adapted to handling the time varying quantities stored on tape, and automatic electronic compilation techniques become possible.

The very great sensitivity of photomultipliers allows the *TSS* to operate at extremely low light levels (see Figure 4). Resolution in the *TSS* is limited only by the size of the object spot on the ground, as determined by the telescopic lens system and not by the characteristics of the storage medium. By narrowing the field, resolution can be made high. However, resolution and the minimum useful light level cannot both be pushed to extremes because they are dependent upon each other and upon a third quantity, the signal-to-noise ratio. Photo-emission is essentially statistical in nature, and for a given available light level there is a probability distribution of the output voltage. The width of this distribution becomes narrower relative to its maximum value (the signal-to-noise ratio becomes higher) when the available light is greater. The width of the distribution of output voltages about the desired or expected signal level is a measure of the "noise" inherent in the system. This noise has a different cause but produces the same effect as those "noises" in conventional photography which arise from lens aberrations, image creeping, emulsion grain size, etc. An optimum choice of signal-to-noise ratio, sensitivity to low light

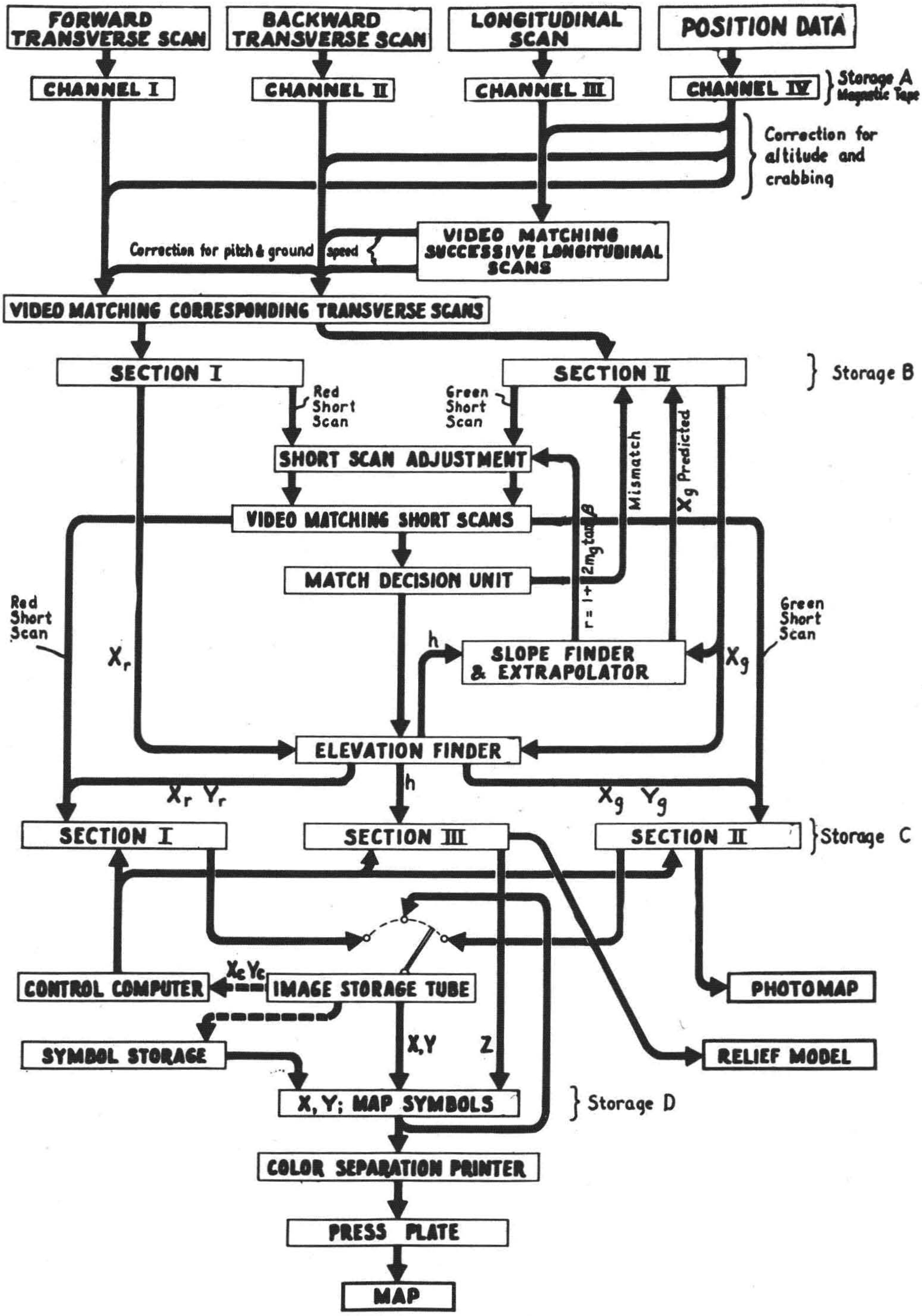

FIG. 1. Block diagram of the PRA Terrain Scanning System.

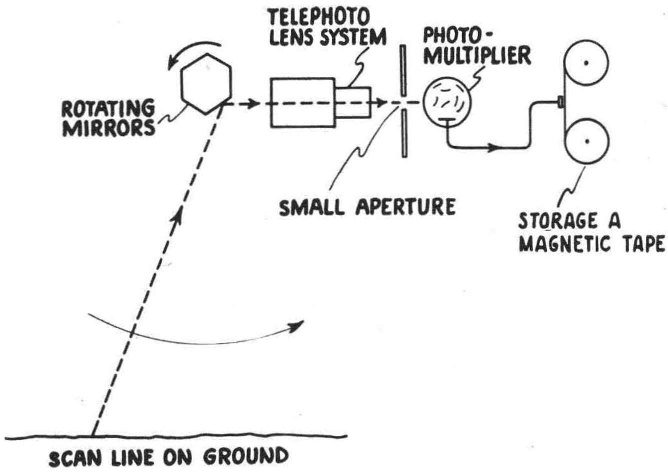

FIG. 2. Airborne scanning components.

intensities, and resolution will give values for all three of these quantities which, for a useful range of flying altitudes, are significantly better in the *TSS* than in the photographic case.

Since the photomultiplier output signal varies in time, the frequency response of the over-all system is important. For a flying altitude of 30,000 feet, an aircraft velocity of 600 m.p.h., and a resolution distance of ten feet between distinguishable objects on the ground, the calculated maximum frequency response required is approximately 450 kilocycles. This speed of response is easily exceeded in photomultiplier circuits, as well as in available TV magnetic recording systems.

When the survey aircraft returns to the ground, the magnetic tapes are attached to the input of the automatic compilation system shown in block diagram form in Figure 1. The airborne tapes for each of the three ground scans are represented in Figure 1 by the first three sections of storage *A*. The fourth section of storage *A* carries continuously recorded altimeter indications and other information as to aircraft position and orientation. Although the amount of information acquired by the scans in a normal mapping flight is very

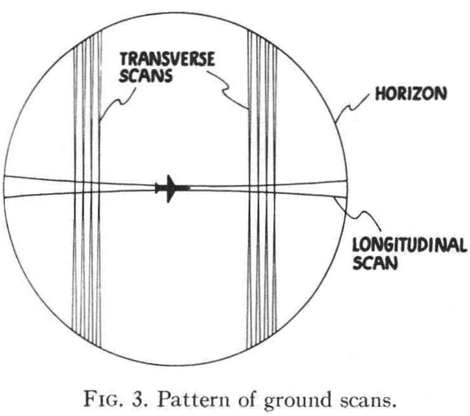

FIG. 3. Pattern of ground scans.

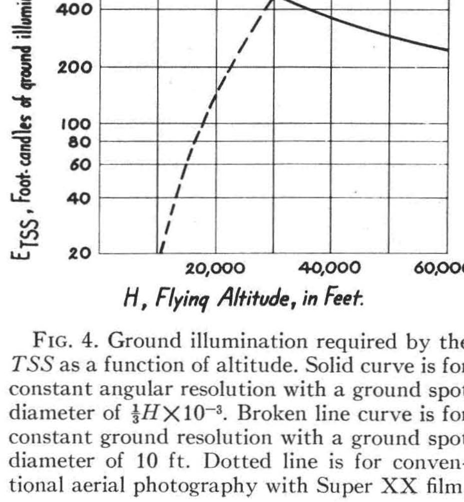

FIG. 4. Ground illumination required by the *TSS* as a function of altitude. Solid curve is for constant angular resolution with a ground spot diameter of $\frac{1}{3}H\times10^{-3}$. Broken line curve is for constant ground resolution with a ground spot diameter of 10 ft. Dotted line is for conventional aerial photography with Super XX film.

large, the required bulk and weight of the tape reels is surprisingly small. A single reel of tape will hold all the information acquired by one of the scans during a normal mapping flight.

As a first step in the compilation process, the transverse scans held in storage *A* must be corrected for irregularities of the aircraft flight. Changes in scale as a result of altitude fluctuations will cause an expansion or contraction of the video wave forms of the longitudinal and transverse scans. The effects of scale variation are removed by expanding or contracting the scan time bases and by varying the separations between adjacent parallel scans. These adjustments are carried out by sending the transverse scans to storage *B* (Figure 1), a magnetic drum storage, and controlling the rate of write-in and the spacing at the drum recording heads in accordance with the previously recorded altimeter readings.

Correction of each scan for the instantaneous effects of crabbing, roll, pitch, and forward and sideward motion (the elements of rectification and orientation) involves great technical difficulty. Conceptually these corrections could be made by differentially expanding, contracting and displacing the video information upon the scan time bases in accordance with measured aircraft orientation parameters (horizon signals, error signals from matching successive longitudinal scans, etc.). Instead, the problem has been approached from the standpoint of suppressing undesired motions of the camera platform within the aircraft. For the remainder of this discussion, it is assumed that the scanning platform is so highly stabilized that, within the limits of accuracy and resolution required, subsequent correction for tilt is unnecessary. Aircraft ground track is measured independently and recorded in channel 4 of storage *A*. The ground track record, in conjunction with the altimeter record, controls the spacing and timing of the read-out from magnetic tape into storage *B* so as to properly orient each new transverse scan with respect to preceding ones. Thus the corrections applied to the tape read-out are merely those of relative displacement and orientation of successive waveforms; deliberate distortion of the waveforms themselves is avoided.

Between storages *B* and *C* in Figure 1, the blocks of the diagram are concerned with the measurement of relief and removal of relief displacement from the transverse scan waveforms. The forward and backward transverse scans which cover the same ground area are compared to find the amount of relief displacement. However, these video wave forms are not compared in the form in which they are held in storage *B*. Instead, a set of "short-scans" is constructed by reading out of storage *B* along short distances in the *X* (longitudinal) direction, whereas the scans originally entered storage *B* in the *Y* (transverse) direction. The reason for this is easily seen from Figure 5. The symmetry of the scanning pattern causes the relief displacement of any given ground point appearing on both the forward and backward transverse scans of storage *B* to be equal and opposite in the *X* direction, and equal and of the same sign in the *Y* direction. Therefore the relative displacement on the forward and backward scans will be greatest in the *X* direction, and the short scans constructed by sampling the original transverse scans in this direction will be most sensitive to the effects of relief. On the other hand, the short scans in the *X* direction (constant *Y*) are insensitive to the *Y* component of relief displacement, because the displacement in this direction is the same for the short scans constructed from sections I and II of storage *B*. Thus, when the proper *X* locations of the corresponding short scans have been established, the similarity of the two short scan waveforms will not be impaired by the *Y* displacements. The matching process is one of searching in the *X* direction for pairs of short scans which carry nearly identical video waveforms. The relative locations of these corresponding short scans indicate the relief displacement, and therefore the amount of relief, which is present.

The short scans are matched in a differential amplifier (video matching short scans, Figure 1) the output of which is the amplified difference of the input voltage waveforms. Actually a sequence of ten short scans lying adjacent to each other in the *Y* direction in the two sections of storage *B* are matched. The resulting difference voltages from the matching of all such pairs are integrated in a storage condenser; the magnitude of this condenser voltage is then a measure of the matching error. Thus sections I and II of storage *B*

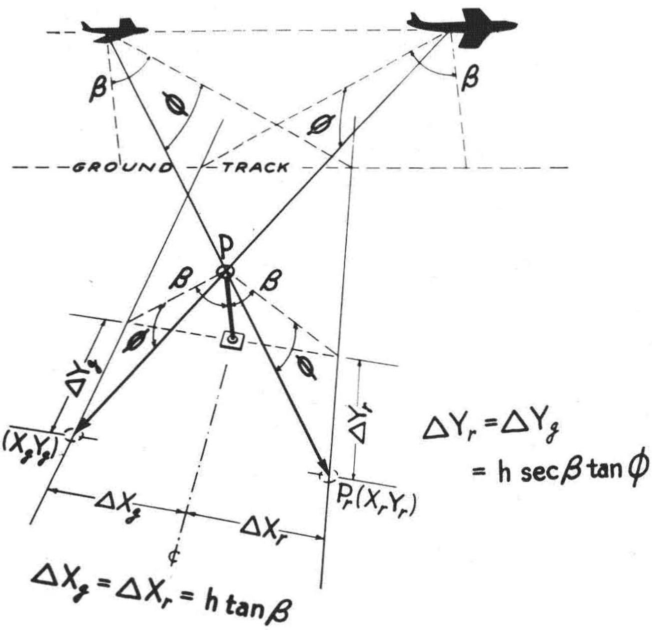

FIG. 5. Relief geometry of the transverse scans.

are compared for relief by matching small square blocks of scan wave forms. The dimensions of the small blocks are approximately ten times the resolution spacing of the information in storage B.

The integrated error from the matching is then sent to a decision unit (Figure 1) which decides whether the error signal lies within or without the tolerance limits for a match. When a good match is not obtained, a mismatch signal is sent to section II of storage B to control the search pattern for subsequent blocks of short scans. When the best match is found, a gating signal is sent to the elevation finder (Figure 1), an analog subtractor and multiplier, which computes the elevation h from the best-matched small block coordinates (in storage B) according to the formula

$$h = \frac{X_{I} - X_{II}}{2 \tan \beta}$$

where

X_{I}, X_{II} = small block coordinates in sections I and II, respectively, of storage B.

β = the stereo angle of the transverse scans.

Prior to matching, the short scan waveforms are deliberately distorted in the short scan adjustment unit (Figure 1) in order to: (1) emphasize object boundaries and suppress indications from areas of little detail; and (2) remove the foreshortening and elongation effects produced by oblique viewing of sloping ground. In the first case, the short scans are enhanced by adding or subtracting derivatives of their waveforms. In the second case, the time base of the short scan from section II of storage B is stretched with respect to the short scan from section I by the factor

$$r = 1 + 2m_{II} \tan \beta$$

where m_{II} = the apparent slope of the ground in the X direction as seen by the backward looking transverse scans (in section II of storate B). The formula for r given above is a valid simplification of a more exact expression that has been derived to relate the time bases of the two short scans.

The elevations h of all points are sent to section III of storage C, where they are stored opposite the appropriate (X, Y) position values. The elevation finder also sends the elevation h to a slope finder (an analog function generator) which compares recent values of h with earlier values in order to find the rate of change m_{II} of h with X. The small blocks of short scans in section I of storage B are treated in sequence in the X direction. Therefore the apparent ground slope m_{II}, as seen by the scans of section II, can be used to predict the most probable X coordinate of the short scans in section II which will match with the next block of short scans in section I. Such a prediction allows an immediate selection, called selective search, of the two blocks of short scans in sections I and II of storage B which are most likely to correspond to each other in information content, and eliminates the need to examine all such blocks in an ordered search pattern. The slope m_{II} determined by the slope finder is also used to find the factor r in time base compensation. The various feedback and control connections between the relief measurement components are shown in Figure 1.

After the relief measurement has been completed, the transverse scans of sections I and II of storage B, are read out of storage B and displaced during their entry to storage C in such a manner as to correct instantaneously and continuously for the known relief displacements ΔX_I, ΔY_I, ΔX_{II}, ΔY_{II}. (ΔY_I and ΔY_{II} are directly proportional to ΔX_I abd ΔX_{II}.) Sections I and II of storage C, a tape-drum storage, are identical. Each stores the terrain information in the form of a magnetization intensity for each (X, Y) position. The video signals represented by the magnetization of sections I and II of storage C now constitute a true orthographic projection of the terrain.

Except for control adjustments, the coordinates of the information in storage C are properly corrected. When adjusting to control, it is necessary that a photo interpreter see the image held in storage C, identity control points, and send their coordinates to a control computer. For this purpose a "black dot method" is used in conjunction with an image storage tube. Blocks of video signals, constituting an image of a portion of the ground, are removed from storage C and presented in raster form as an area display on an image storage tube (a cathode ray tube designed to show and hold a static image on its face). A black dot is produced on the face of the image tube by generating a short negative pulse and applying it with a variable time delay to a control grid of the tube. The time delay is adjusted manually by the photo interpreter so that the black dot coincides with an object of interest. The coordinates in storage C of control points, automatically provided by the black dot time delay, are sent to the control computer. It is the function of the control computer to compare these coordinates with ground survey values. Discrepancies between the control point coordinates in storage C and the ground survey values define a four dimensional "error surface" (plot of the three dimensional vector position error versus X) for all points of the map strip. The computer can be required to find a straight polynomial solution to the errors obtained, or a best fit for a particular "error surface" (characteristic of a mapping process) containing adjustable parameters. The "error surface" can be made to pass through the known errors at all control points, or , by reducing the order of the polynomials constituting the "surface," a smoother shape can be obtained which is a best fit to the errors at the control points. This procedure simultaneously corrects for Z as well as (X, Y) values, thereby providing all corrections as the solution of a single control problem.

At this point in the mapping operation, the readjusted signals in storage C can be used to print a photomap or carve a relief model. The photomap (not to be confused with the familiar photomosaic) is a fully corrected orthographic projection of the terrain. It can serve as an end product of the map compilation operation, or it can be used as a master manuscript for making overlays and producing a color map in the usual reproduction manner. Alternatively, the map manuscript can be prepared by placing map symbols semi-automatically, as indicated by the blocks at the bottom of Figure 1.

To produce a photomap, the video signals of section I or II, storage C, modulate a light source which is focused to a small spot on photo-sensitive paper mounted upon a rotating drum. Variation of the light intensity produces the proper tone shades, as the light source scans the paper in a pattern corresponding to the read-out pattern from storage C. This method is very similar to that used in the printing of facsimile copy. The photomap scale can be changed by changing the diameter of the facsimile drum and the pitch of the drive mechanism.

Section III of storage C is a compact source of information for the automatic construction of relief models. Section III contains elevation values for each (X, Y) position. Hence a cutting or forming tool can be made to move through plastic, wax or other material so as to produce automatically an accurate three-dimensional model. The tool is moved in the X and Y directions in accordance with the read-out pattern from section III, while the vertical motion of the tool is controlled by the elevation values recorded at the various (X, Y) positions in section III. In this manner the tool scans uniformly in the X and Y direction while cutting profiles by its vertical motion. A contour cutting operation is also possible, but is less desirable than the profile operation just described because the contour operation abandons the simple sequential read-out for a more complicated read-out pattern from section III of storage C. Any arbitrary vertical exaggeration can be selected for the Z motion of the cutting tool in either the profile or contour operation.

Considerable engineering development of the *TSS* is still required to provide the necessary stability and ground track information for the airborne scanner and to reduce the electronic complexity of some of the ground-based equipment. However, the preliminary design indicates that map accuracy standards can probably be maintained. Size and weight of the airborne components of the *TSS*, including the magnetic tape, are practical for installation in survey aircraft.

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