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The Control Point Library Building System

The CPLBS, developed for the geometric correction of Landsat MSS and RBV imagery, has attained accuracies of better than one-fourth of a pixel.

ABSTRACT: *The Earth Resources Observation System (EROS) Data Center in Sioux Falls, South Dakota distributes precision corrected Landsat MSS and RBV data. These data are derived from master data tapes produced by the Master Data Processor (MDP), NASA's system for computing and applying corrections to the data. Included in the MDP is the Control Point Library Building System (CPLBS), an interactive, menu-driven system which permits a user to build and maintain libraries of control points. The control points are required to achieve the high geometric accuracy desired in the output MSS and RBV data. This paper describes the processing performed by CPLBS, the accuracy of the system, and the host computer and special image viewing equipment employed.*

INTRODUCTION

EARTH IMAGE DATA are gathered by several satellite-mounted sensors such as the MSS and RBV sensors on the Landsat satellites. These data are processed to produce photographs and corresponding digital products of the surface of the Earth, and these are used by cartographers, photointerpreters, and scientists in numerous applications. Much of the processing is concerned with removing geometric distortions inherent in the raw data, for example, the distortion due to the curvature of the Earth.[1,2] In order to perform this processing accurately, one must utilize 'ground control points' (GCP's). A GCP is a small window of data containing a feature, such as a road intersection, whose geodetic coordinates (latitude and longitude) are accurately known. If a number of these points can be found in the data, a transformation can be derived to correct the data to produce the accurate photographs and digital products. For a satellite system with near world-wide coverage such as Landsat, over 200,000 control points need to be generated, organized, and stored in a data base. These are the functions of the Control Point Library Building System.

BACKGROUND CONCEPTS

ACRONYMS

Several acronyms are used repeatedly in this paper and are listed here for reference.

CPLBS—Control Point Library Building System.

MDP—Master Data Processor. The hardware/software system at the NASA Goddard Space Flight Center in Greenbelt, Maryland for the correction of MSS and RBV images.

MSS—Multispectral Scanner. One of the two sensors on the Landsat satellite.

RBV—Return Beam Vidicon. The other sensor (in addition to the MSS) on the Landsat satellite.

WRS—World Reference System. A coordinate system defined to facilitate the processing of Landsat data. The surface of the Earth was divided into WRS "scenes" based on the Landsat orbit. Each scene is about 100 n. mi. square (185 km square). In order to cover the surface of the Earth viewed by the Landsat satellite, 251 paths of 248 rows, or 62,248 scenes, are required.

IDT—Image Display Terminal. A Ramtek 9300 Graphic Display System with Conrac monitor on which displays of image data are presented. It is a 32 grey-level 512 by 640 display.

CLA—Control Location Algorithm. An algorithm using forward and inverse Fast Fourier Transforms which automatically locates the digital representation of a control point in an area of an image. (See section "Processing Environment".)

SCP—Supplemental Control Point. A control point which a user selects from a scene and for which latitude and longitude information were not scaled from a map. (See section "The Need for Supplemental Control Points.")

ZTS—Zoom Transfer Scope. An optical mechanical

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device which permits an image on the IDT and a map to be superimposed and viewed simultaneously. The ZTS is a modified Bausch and Lomb model ZT-4.

PROCESSING ENVIRONMENT

When in digital form, the MSS and RBV image data are an array of numbers, each number representing the radiance or brightness of a portion of the Earth. For input MSS data, each number, or "pixel," represents a square on the Earth 80 metres on a side. Because of the viewing angle, properties of the sensor, spacecraft attitude, etc., the geometry of the original data is distorted. One of the primary functions of the MDP is to process the data to produce output products with the correct geometry.[3,4] Certain distortions in the data, such as those due to the curvature of the Earth, may be removed based on equations derived from the satellite orbit and viewing angle. Others, due to the spacecraft attitude, require accurate values of the attitude. For Landsat, sufficiently accurate attitude estimates are not a priori available. As a result, these distortions must be modeled using control points locatable in the data and of known geodetic location. Such points are generated and stored in the control point library.

A control point consists of a 32 pixel by 32 line array containing a feature, and descriptive data about the array, particularly the latitude and longitude of the feature. To correct the input image data, MDP reads the data and selects the appropriate control points from the library. For each control point, an estimate of its location in the input image is made. An area around the estimated location is automatically searched for the point of highest correlation with the control point window using the "Control Location Algorithm" (CLA). The point of highest correlation gives the image location (line and sample) of the feature. Its latitude and longitude are known since it is part of the data generated by CPLBS and stored in the library. These line/sample and latitude/longitude coordinate pairs are used to compute parameters describing the distortions in the data. These parameters then drive other functions which produce the corrected output products.

GEODETIC REGISTRATION AND TEMPORAL REGISTRATION

The MDP performs two kinds of geometric corrections—geodetic registration and temporal registration. The object of geodetic registration is to register an image with a geodetic standard, i.e., a map. Control points used in geodetic registration have been assigned a geodetic location (latitude and longitude) and are called "ground control points."

The object of temporal registration is to register an input image with another image of the same ground area called the "reference image." Such registered images can be used for change detection. Control points used to perform temporal registration are called "temporal control points." Instead of accurate geodetic coordinates, temporal control points have assigned to them their coordinates relative to the reference image.

Hardware

As described in the next section, one of the main functions of the CPLBS is to allow a user to locate, within the image data, features marked on a map. To do this, CPLBS uses a set of hardware known collectively as a workstation. A workstation consists of

- an IBM 3277 Display Station with keyboard (the alphanumeric terminal),
- a Ramtek 32 level 9300 Graphic Display System with cursor and joystick (512 lines by 640 pixels),
- a Conrac video monitor (the IDT), and
- a Bausch and Lomb model ZT-4 Zoom Transfer Scope modified to view the Conrac monitor and adjusted to provide a 3× map magnification.

The IBM 3277 is used to display menus and to communicate commands and data from the user. Images, sent from the host to the Ramtek, are displayed on the IDT, and, by using the cursor, a user may designate a point within the image. The ZTS is a stand-alone optical-mechanical instrument which permits a user, looking through the binocular eyepiece, to view simultaneously a map placed at its base and an image on the Conrac monitor. The workstation configuration, including the host computer, is shown in Figure 1.

The MDP computer, which hosts the CPLBS, consists of the IBM Advanced Signal Processor[5] and a set of standard and special input/output (I/O) devices and control units. The Advanced Signal Processor is a special purpose computer for signal and image processing applications. It contains a general purpose control processor, a special arithmetic processor, a large overlapped bulk store, and a high-capacity I/O bus structure. The arithmetic processor performs fixed-point 16-bit operations with two high-speed pipelined arithmetic elements which execute in parallel, each having an instruction cycle time of 100 ns per add and multiply pair. Bulk store, the major internal data storage, contains 256k 32-bit words.

On-Line Processing Description

All CPLBS processing is concerned with the generation, updating, and maintenance of the sets of ground control points and temporal control points stored in the control point library. This section walks through the interactive process necessary to generate a set of ground control points for MSS data. The process is summarized in Figure 2. For full details on any of the steps, including equations or specific algorithms, see reference 6.

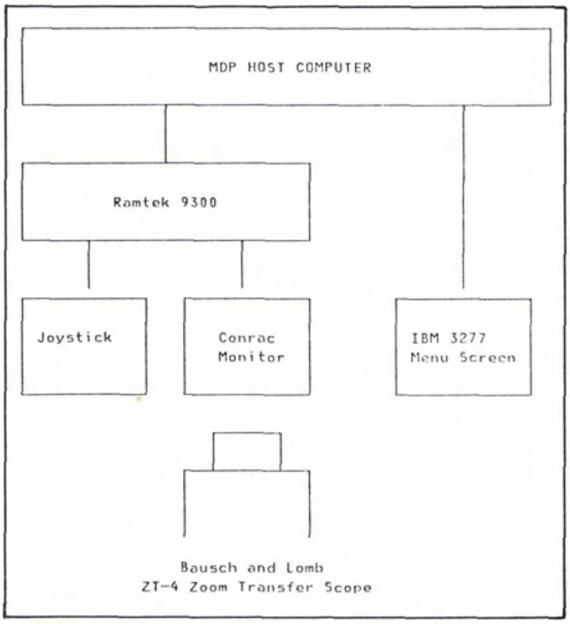

FIG. 1. CPLBS workstation configuration.

DATA PREPARATION AND INPUT

The first step is selecting and preparing the input data. The user selects an input scene of the ground area for which the control point set is to be generated, obtains transparencies and image data tapes of the scene, and obtains maps covering the area. Ground features visible in transparencies of the scene and on the maps are identified. The features on the map are precisely marked and the geodetic coordinates of the points are scaled from the map. A tape, called a GCP tape, is generated which contains, for each point, its latitude and longitude, the scale of the map, a control point identification number, and other supporting information.[7]

When the GCP tape has been prepared, the user is ready to begin an interactive session. He signs on at the CPLBS workstation, which includes the alphanumeric terminal to present menus, and the image display terminal to present image data. The map control points, or simply map points, are read from the GCP tape. The image data are read and several distortions, such as the variation in line length, are removed so that they will not introduce inaccuracies in the subsequent Point Location function. From the image tape, CPLBS also reads the available ancillary data such as initial estimates of spacecraft orbit and attitude as it imaged the data.

POINT ESTIMATION

For each map point read, CPLBS estimates its location within the input image. This estimation begins with the latitude and longitude read from the GCP tape. It uses the ancillary orbit and attitude data and models of the viewing geometry and sensor properties to produce, for each point, an estimated line and sample coordinate within the input image. The estimation consists of mapping each point through a series of equations modeling the various distortions present in the data. One of these is the distortion due to the satellite attitude, and this is the only equation for which the correct coefficients are not accurately known. However, as a result, the line and sample coordinates of the points may be off, in the worst case, by up to 50 pixels.

PROCESSING STEP	OBJECTIVE
Data Preparation and Input	Read the file of map points, read the Landsat image data
Point Estimation	Estimate an image line/pixel for each map point
Point Location	Accurately locate each point by manually placing the cursor on the correct image location
Attitude/Altitude Modeling and Blunder Detection	From the coordinates found manually above, derive accurate equations relating line/pixel to latitude/longitude
Suitability Checking	"Weed out" points which will not perform well in the automatic control point location algorithm
Distribution Checking	Identify areas of the image which do not contain control points
Supplemental Control Point Selection	Select points in the areas that do not have any
Entry of Points into Library	Store the generated set in the library
OVERALL OBJECTIVE:	Store in the library a set of control points which are: -accurately located -sufficient in number -well distributed -suitable for use in the automatic control location algorithm

FIG. 2. CPLBS interactive processing summary.

POINT LOCATION

This next step involves refining the locations of the control points from the plus or minus 50 pixels to approximately plus or minus 1/4 pixel. The user does this by manually locating the points in the displayed image data.

Locating each map point consists in accurately placing the cursor on the point as it is displayed on the IDT. Initially, the system presents on the IDT the "Small Scale Display." This is a single-band, shade-of-grey display in which each pixel is presented as one raster position on the screen. Thus, for the 640 line by 512 sample screen size used, a 640 line by 512 sample subimage of the input data is displayed. Given the scale of the MSS data and the physical size of the image screen, this display is of approximate scale 1:166,000 vertically and 1:122,000 horizontally.

As the image data are displayed on the IDT, the "Small Scale Display Menu" (Figure 3) is presented on the alphanumeric terminal. Referring to the marked map and the transparency, the user searches for the map point. If he cannot find the point, he has three options. He may perform a radiometric enhancement to bring out the feature (the enhancement is a linear adjustment—a gain and bias—implemented by computing a translate table for the pixel values and writing this table to a special auxiliary memory in the IDT), he may display the feature in a different spectral band, or he may reject the point. If he can identify the point, he places the cursor on it and selects the option to expand the feature. In this case, CPLBS reads the data surrounding the cursor position and performs a digital expansion using cubic convolution resampling. The expansion factor applied to the image data is derived from the scale of the map (previously read from the GCP tape), the scale of the MSS data, the physical screen size, and the optical properties of the Zoom Transfer Scope (ZTS). It is computed so that the displayed image is at the same scale as the map as seen through the ZTS. In the existing equipment, the ZTS is adjusted to provide a 3× magnification in the map lens so that, as an example, for a point marked on a 1:24,000 scale map, the displayed image is expanded to 1:8000. Typical values of the expansion ratio and required number of input pixels are shown in Table 1. The expanded data are presented on the IDT, and the "Large Scale Display Menu" (Figure 4) is presented on the alphanumeric terminal. The user places the map at the base of the ZTS and, viewing the map and image simultaneously through the binocular eyepiece, he precisely aligns the two and attempts to locate the marked point from the map in the image display. If the user cannot align the map or locate the point, he may change bands, perform a radiometric enhancement, reject the point, or return to the small scale display. If he can locate the point, he moves the image cursor to the location over the point marked on the map, and by selecting the appropriate option from the "Large Scale Display Menu," causes CPLBS to record the image coordinates of the point. Notice that when the user locates a point using this process, he is identifying its image coordinates to sub-pixel levels. For example, when using a 1:24,000 scale map, each raster position on the screen corresponds to approximately 1/20 of an image pixel in the line (vertical) direction.

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Small-Scale Display Menu

1  Display large-scale sub-image centered on cursor
2  Reject this map point and proceed to next
3  Re-display in a different band (enter band)
4  Enhance image (enter gain,bias - xxx,xxx)
5  Re-position cursor at estimated control point location
R  Return to map point location control menu
```

FIG. 3. Options in the small scale display.

THE NEED FOR SUPPLEMENTAL CONTROL POINTS

When all map points have been processed (either located or rejected), those that have been located could be entered into the library since all the basic data are available: their latitude and longitude were read from the GCP tape, and the exact location within the image data around which to extract the 32 line by 32 pixel window has been tagged by the user. However, experience has shown that map points located by the user do not necessarily perform well when input to the CLA during MDP processing, which is, after all, the purpose of the control points. To minimize this problem, CPLBS performs two additional functions: (1) suitability checking, and (2) selection of supplemental control points (SCP's). Suitability checking estimates whether the window around a feature will perform consistently well in the CLA when used by the MDP. Several of the map points may be found unsuitable and are deleted. However, since a scene must include about 20 points to enable MDP to perform an accurate correction, additional "supplemental" points may be selected. A sup-

TABLE 1. LARGE SCALE DISPLAY PARAMETERS: (V = VERTICAL OR LINE DIMENSION H = HORIZONTAL OR SAMPLE DIMENSION)

Map Scale	Expansion Ratio MSS		Expansion Ratio RBV		Number of Input Pixels in the Display MSS		Number of Input Pixels in the Display RBV	
	v	h	v	h	v	h	v	h
1: 24,000	20.7	15.2	6.2	4.8	26	42	82	134
1: 62,500	7.9	5.8	2.4	1.8	64	109	213	349
1:250,000	2.0	1.5	—	—	129	219	—	—

```
Large-Scale Display Menu

1  Enter control point at cursor location

2  Reject present map point and proceed to next

3  Re-display in a different band (enter band)

4  Enhance image (enter gain,bias - xxx,xxx)

5  Re-display small-scale subimage
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FIG. 4. Options in the large scale display.

plemental control point is simply any point designated by the user from a display of the image. Selection of SCP's permits the user to tag any feature in the input image as a candidate control point.

Points are either map points or supplemental points. A map point has its latitude and longitude read from the GCP tape and is located by the user using the maps and Zoom Transfer Scope. In order to select and store SCP's in the library, a method of assigning latitude and longitude coordinates to them is necessary. Just as equations were used to transform the latitude and longitude of the map points to line and sample to originally estimate their image location, so the inverse equations can be used to transform the image line and sample of a selected SCP to latitude and longitude. For the latter case, a highly accurate model is required. Such a model was not available when the input tape was read and is the reason the initial estimates of image coordinates were off by up to 50 pixels. However, an accurate model can now be derived from the set of located map control points if a sufficient number (15 to 20, depending on their distribution) have been located. Therefore, the process is as follows:

- Using the attitude and altitude models based on ancillary data, estimate in the input image the locations of the map control points (Point Estimation, described above);
- Using the marked maps and the IDT/ZTS, locate the map points in the input image (Point Location, described above);
- Using the located positions, derive new attitude and altitude models which more accurately describe the spacecraft orientation (Attitude/Altitude Modeling, described below);
- Select SCP's and assign their latitude and longitude based on the derived, accurate models (Selection of Supplemental Points, described below); and
- Check the suitability of all selected points, map and supplemental, to predict whether they will perform well in the CLA when used by the MDP (Suitability Checking, described below).

Notice that this method frees the user to select any point within the image as a potential control point simply by designating it with the cursor.

ATTITUDE/ALTITUDE MODELING

In attitude/altitude modeling, CPLBS computes the coefficients of a model of the attitude and altitude of the spacecraft as it imaged the scene. For the MSS, which scans continuously and takes about 25 seconds to gather data for one scene, cubic polynomials in time are derived for each of roll, pitch, and yaw. The coefficients are computed by a least-squares fit to the located map point data. If the number and distribution of the located map points are sufficient, the coefficients provide a highly accurate estimate of the spacecraft attitude.

To improve the accuracy, a blunder detection algorithm is used. A blunder is a gross error in the location of a map point which may result from a user error, e.g., locating a nearby road intersection instead of the correct one, or a transposition of digits in recording the latitude and longitude when generating the GCP tape. The least-squares fitting algorithm used to model the attitude and altitude permits a blunder detection algorithm to be applied to the located control points. The algorithm is as follows:

(1) Compute the residuals of the control point locations after the fit.
(2) Compute the standard deviation of the set of residuals.
(3) If the standard deviation of the set of residuals exceeds a threshold, delete the point with the largest absolute residual as a blunder.
(4) Otherwise, delete any point whose residual exceeds k times the standard deviation of all residuals where k is adjustable (e.g., perform a three-sigma check).

Step 3 is intended to identify systematic or repeated blunders, whereas step 4 identifies a small number of blunders in a generally well-located set.

If a point is identified as a blunder, the attitude/altitude modeling is repeated using only the non-blunder points, and the blunder check is repeated until no additional blunders are found. The blunder check results are displayed to the user, who may relocate or discard the points identified as blunders.

SUITABILITY CHECK

As each point is located by the user, it is evaluated with respect to "suitability." The suitability check attempts to predict how likely the point is to be accurately and reliably located by the MDP when used in the CLA. For example, windows which contain features with insufficient size or contrast, or in which the range and distribution of pixel values result in a loss of precision in the lengthy CLA algorithm, are poor candidates for control points.

The suitability check consists of computing the discrete autocorrelation function of a window with the surrounding area. Around the maximum value of this correlation matrix a 5 by 5 sub-matrix is extracted, and to these 25 values, a bivariate fourth degree polynomial is fit. The maximum of this polynomial, called the peak, and the minimum curvature at the peak, are the parameters used to estimate suitability. (Curvature here is as defined mathematically, equal to one over the radius of curvature.) A point is judged suitable if the peak height, nominally 1.0, and curvature are within specified thresholds, and the correlation peak is properly located. All results from the suitability check are presented in a menu and the user may delete points or reinstate deleted points as he chooses.

DISTRIBUTION CHECKING

In order for the MDP to obtain the desired geometric accuracy when processing a scene, the control point set for the scene must contain points well distributed throughout the scene. After the map points have been checked for suitability, the distribution of the remaining points is displayed (see Figure 5). In the menu, the image is divided into a 5 by 5 grid of mesh areas, and the number of points in each mesh area is displayed. Each mesh area corresponds to a full screen of data (512 lines of 640 pixels) and together all mesh areas cover the input image.

A maximum of 25 points may be selected for the MSS, including the remaining map points. As a general rule, one point per mesh area is desired. The user can select mesh areas to process, either to add a supplemental point or to delete points if multiple points exist, in order to improve the distribution. If the number of points selected is greater than 25, the system prompts the user to delete points of his choosing.

SUPPLEMENTAL CONTROL POINT SELECTION

When the user selects a mesh area in the "Supplemental Points Selection Menu," the image data for the mesh area is displayed on the IDT. Each existing point is marked in the display. To generate additional points, the user selects features directly from the image by placing the cursor on the feature. If the point passes the suitability check it is accepted and latitude/longitude coordinates are computed for it. The user may delete or reinstate any point in the mesh area using menu options. For each point he selects, the user enters a "generic code" characterizing the feature such as road intersection, dam, etc. By maintaining these codes, CPLBS provides additional data on the type of point which performs well in the CLA.

When the user completes the processing of each mesh area, the "Supplemental Points Selection Menu" is redisplayed. The 5 by 5 matrix of the point distribution is updated to reflect the points added or deleted, and the user may designate further mesh areas to process, or he may terminate supplemental point selection.

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              Supplemental Points Selection Menu

 1  Display next mesh area which contains no points

 2  Display specified mesh area (enter mesh area - x,x)

 T  Terminate processing of this control point set

             Total number of points = 14

              1     2     3     4     5
           * * * * * * * * * * * * * * * * *
         1 *  0     1     0     0     0    * 1
           *                               *
         2 *  1     0     3     1     0    * 2
           *                               *
         3 *  0     1     0     2     1    * 3
           *                               *
         4 *  2     0     0     1     0    * 4
           *                               *
         5 *  0     0     1     0     0    * 5
           * * * * * * * * * * * * * * * * *
              1     2     3     4     5
```

FIG. 5. Supplemental points selection menu.

ENTRY OF POINTS INTO THE LIBRARY

Termination of Supplemental Point Selection completes processing for a scene. A window for each control point is extracted from the input image data, supporting data fields are formatted, and the control point records are added to the control point library. A summary/analysis report is printed which includes information about the input scene, the computations performed, and all points processed.

The interactive process described above, from reading in the input tapes to storing the points in the library, takes about two to three hours. The most time consuming portion of the process is Point Location, and the above estimate is based on scenes in which 20 map points were located.

GENERATION OF TEMPORAL REGISTRATION CONTROL POINT SETS

In addition to the ground control points discussed above, temporal control points are maintained in the control point library. Such points are used by the MDP to perform temporal registration. A temporal control point set contains points located in one specific reference scene and is identified by a WRS path and row number plus the reference scene identifier.

When generating a temporal control point set, the user selects a well-distributed set of points in a corrected reference scene. CPLBS extracts windows for these points from the image data for the scene, and assigns coordinates to these points based on their position in the scene. No map control points are needed since the ancillary data on the input tape contains all the parameters used to correct the reference scene, and this information allows CPLBS to assign to selected points their exact coordinates relative to the reference scene.

ACCURACY

The accuracy of CPLBS processing is directly dependent on the accuracy with which a user can locate map control points in the expanded image data using the Zoom Transfer Scope (ZTS). The largest error source arises from the inability to precisely align the marked map with the displayed data. An analysis of the error sources in the process gave the values shown in Table 2. These values agree with empirical results in that the residual errors from the attitude/altitude fit are essentially a measure of the total error, and they have typically been in the range of 15 to 22 metres (one sigma) for MSS data when using predominantly 1:24,000 scale maps. Notice that these figures are well below pixel size (approximately 80 metres for MSS), reflecting the sub-pixel accuracy which can be obtained using CPBLS.

Ultimately, the accuracy of CPLBS is reflected in the geometric accuracy of the corrected MSS and RBV images generated by the MDP. During testing of the MDP MSS system, well-distributed control point sets were generated using the CPLBS, and these were used to correct selected scenes. The corrected scenes were measured to have geometric accuracies such that 90 percent of all points had positional error less than 23 metres in both line and sample, including the measurement error. That is, the 23-metre figure, in addition to any error in the control points, includes the errors in the CLA location, in the MDP geometric correction (both very small errors), plus the error inherent in the measurement process (approximately 18 metres).

Table 2. Total Error in Located Map Points

Map Scale	Standard Deviation of Total Error in Meters MSS	RBV
1: 24,000	18.0	14.9
1: 48,000	36.0	24.5
1: 50,000	37.5	25.5
1: 62,500	46.9	31.9
1:125,000	95.2	n/a
1:250,000	190.5	n/a

Summary and Conclusions

CPLBS is the operational production system used at NASA GSFC to generate control point sets for the processing of MSS and RBV data. For both sensors, it permits the generation of ground control points and temporal control points. On-line processing is directed by a user who selects menu options and views displays of image data on a monochromatic vidicon monitor. At the heart of the system is the process of locating features marked on a map within the displayed data. This is accomplished by viewing the superimposed map and image data through the binocular eyepieces of the Zoom Transfer Scope. Because the image data are expanded for these displays, the image coordinates of the ground features are located to sub-pixel levels of accuracy. An extensive set of menus permits flexible and highly accurate control point location and selection. Included are functions to detect user errors in locating points and to screen points that have a poor predicted performance in the automatic control location algorithm. Using the generated sets, MSS images can be corrected to better than 20 meters RMS—approximately one-fourth of a pixel.

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