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Final Report

CARTOGRAPHIC MAPPING STUDY

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16. Abstract

The errors associated with planimetric mapping of the United States using satellite remote sensing techniques are analyzed. Assumptions concerning the state of the art achievable for satellite mapping systems and platforms in the 1995 time frame are made. An analysis of these performance parameters is made using an interactive cartographic satellite computer model, after first validating the model using Landsat 1 through 3 performance parameters. An investigation of current large scale (1:24,000) US National mapping techniques is made. Using the results of this investigation, and current national mapping accuracy standards, the 1995 satellite mapping system is evaluated for its ability to meet US mapping standards for planimetric and topographic mapping at scales of 1:24,000 and smaller.

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1.0
INTRODUCTION

This report describes the work performed under NASA contract NAS 5-26820, a project entitled Cartographic Mapping Study. The purpose of the study is two fold:

1. Determine the techniques used in the generation of maps of the United States, the standards used, and provide a "primer" describing the process. (This primer is included as Appendix A).

2. Perform an analysis of satellite mapping to determine if National Mapping accuracies can be achieved for 1:24,000 scale maps by 1995, and what role satellite remote sensing can play in the mapping program.

A more detailed description of the background of the program, and the problem addressed is in Section 2. Section 3 briefly describes the mapmaking process, with a more detailed description in Appendix A. Section 4 describes the conduct of the analysis portion of the study. A source listing of the interactive Fortran program which was used to perform tradeoffs of system design parameters during this portion of the study is included as Appendix B. The conclusions reached after the conduct of the study are presented in Section 5.

2.0
BACKGROUND AND STATEMENT OF THE PROBLEM

Since its inception, one of the stated and/or implied intended applications of the Landsat series of satellites has been large area mapping. In practice, little actual mapping has been done using Landsat until recently because techniques did not exist which permitted independent or semi-independent map generation which would meet any accepted mapping standards. In the recent past, advancing technology has made it feasible to use Landsat data, at smaller scales, to generate maps in relatively unmapped areas. Increasing sophistication among users has led to increasing demands for accurate cartographic products derived from Landsat and has led NASA to initiate investigations of mapping needs, and the ability of spaceborne sensors to meet these needs in the future. To some extent, these investigations have led to an amount of confusion because lack of background in cartography and the mapmaking process has made it difficult to identify the key issues that will affect use of satellite data for mapping and the key organizations which must be convinced to adopt the technology. For this reason, a project to investigate the mapmaking problem in terms of techniques currently used and accuracies required, and to investigate the projected future ability of spaceborne sensors to meet current and future requirements appeared in order.

2.1 BASIS OF STUDY

Even a cursory examination of map production by the United States Geological Survey would show that the majority of the mapping activities for new maps at the present and projected into the future are at scales of 1:24,000 or 1:25,000. Further, smaller scale maps are always compiled from the largest scale standard maps available. For instance, a map published at a scale of 1:250,000 is ultimately traceable to the largest scale national map available which today would be either

1:62,500 or 1:24,000 since all of the United States is mapped at one of these two scales. Further, if the current production rate is continued and future planned production is met, all of the United States will be mapped at 1:24,000 or the metric scale of 1:25,000 by the year 1988. New maps after that date will be revisions of 1:24,000/1:25,000 scale maps and compilation of smaller scale maps will be made from those scales. Consequently, if satellite mapping systems wish to contribute to the national mapping program, the systems must be prepared to contribute to the program at the 1:24,000 or 1:25,000 scale level. This will be true whether the contribution is for original map compilation or for revision.

Over the last two to three years, there has been a considerable increase in the use of Landsat MSS data for the generation of digital cartographic products. ERIM has been in the forefront of development of geometric correction techniques for such data, and it is believed that the techniques currently in use at ERIM represent the existing state of the art. Under ideal conditions, cartographic accuracies with RMS errors as low as 20-30 meters have been achieved; however, more typical accuracies under production mapping conditions have been 100 to 150 meters RMS for multiple scene mosaics. With continued refinement, incorporating presently known improvements, these production errors could be reduced to 40-50 meters. This accuracy is sufficient to meet U.S. National Mapping accuracy standards for scales of 1:200,000 or smaller. The standard is location of a point within 1/50 inch (0.5 mm), 90% of the time, at the scale of the map. 90% is approximately two sigma. The equivalent one sigma value is 0.25 mm. 50 meters at 0.25 mm is a scale of 1:200,000.

To be a major contributor to the national mapping program, land remote sensing systems must be capable of generating or revising maps at scales up to 1:24,000. At this scale, map accuracies in the vicinity of 6.1 meters RMS are required. A major objective has been established as the ability to achieve national mapping accuracy standards for this scale with spaceborne scanners by 1995. The basis of this study is the determination of the sensor or mission performance parameters required to meet this objective. The tasks to be performed are listed in the next paragraph.

2.2 TASKS TO BE PERFORMED

The overall objective of this study is to determine the performance characteristics required for both the sensor system and the overall mission to meet national mapping accuracy standards for 1:24,000 or smaller scale maps using satellite remote sensing techniques. To accomplish this objective, a series of four tasks are to be performed:

Task 1: Investigate and report on techniques currently used to generate 1:24,000 - 1:25,000 scale maps, including the sources of the information, the sources of errors, the minimum acceptable and desired accuracies, and methods of compilation and printing. Also investigate and report on techniques for updating such maps, including criteria for updating, sources of information, and methods of incorporation. Determine possible techniques for updating maps using satellite data rather than complete regeneration of the maps.

Task 2: Develop a model of the total satellite mapping system including the sensor itself, the satellite carrier, the ground processing system, and the mapmaking process. Identify and list sources of error in the generation of maps from orbital sensors that would affect the ability to achieve national mapping accuracy standard for maps of scales of 1:24,000 and smaller. Identify and list ancillary data requirements external to the satellite system (such as topographic data for mapping without stereographic coverage).

Task 3: For planimetric mapping, perform a parametric analysis of the effects of the identified error sources upon the accuracy of planimetric maps generated from satellite data. Based upon analysis of the relative effects of the error source upon planimetric mapping accuracies, and reasonable assumptions of the achievable state-of-the-art by 1995, assign an error budget to each major aspect of the total mapping system to operationally achieve national mapping accuracy standards for 1:24,000 or smaller scale planimetric maps by 1995.

Task 4: Investigate use of satellite data for topographic mapping. Determine the system requirements to generate topographic data for sufficient accuracy to (a) achieve topographic accuracy required by the topographic error budget for planimetric accuracy in Task 3 above; and (b) achieve topographic accuracy required to meet national mapping accuracy standards for topographic maps at scales of 1:24,000 and smaller.

3.0
THE MAPMAKING PROCESS

There are many types of maps generated annually in the United States by a number of federal, state, local, and private organizations. Planimetric and topographic maps of land areas at the national level are usually traceable to base maps generated by the United States Geological Survey, (USGS) which generates maps at scales of 1:24,000 and smaller to national standards for sale to the general public and interested organizations. The most commonly used general purpose maps are at scales of 1:250,000, 1:62,500 and 1:24,000. Historical data on map production at various scales by USGS is included in Appendix A, which describes USGS chart production in detail. Regardless of the scale of maps under consideration, the information content of maps produced by USGS is ultimately traceable to the largest scale national map of the area in question. For the major portion of the United States (except Alaska), this largest scale is 1:24,000. Current plans indicate that by 1988, all of the conterminous United States will be mapped at 1:24,000 or its metric replacement scale of 1:25,000. In the interim, portions of the United States must use the scale of 1:62,500 as the largest nationally available scale. The process of producing the charts is shown in Figure 1, which is also Figure A-8 of Appendix A.

3.1 ORIGINAL MAPPING

Original mapping is compiled at a scale of 1:24,000 using stereo photography collected by aircraft. The photography has been collected at higher and higher altitudes with better and better cameras. At present, mapping photography is being collected at altitudes of up to 50,000 feet at scales of up to 1:100,000.

This aerial photographic step is directly analagous to spaceborne data collection. However, most studies directed at use of spaceborne

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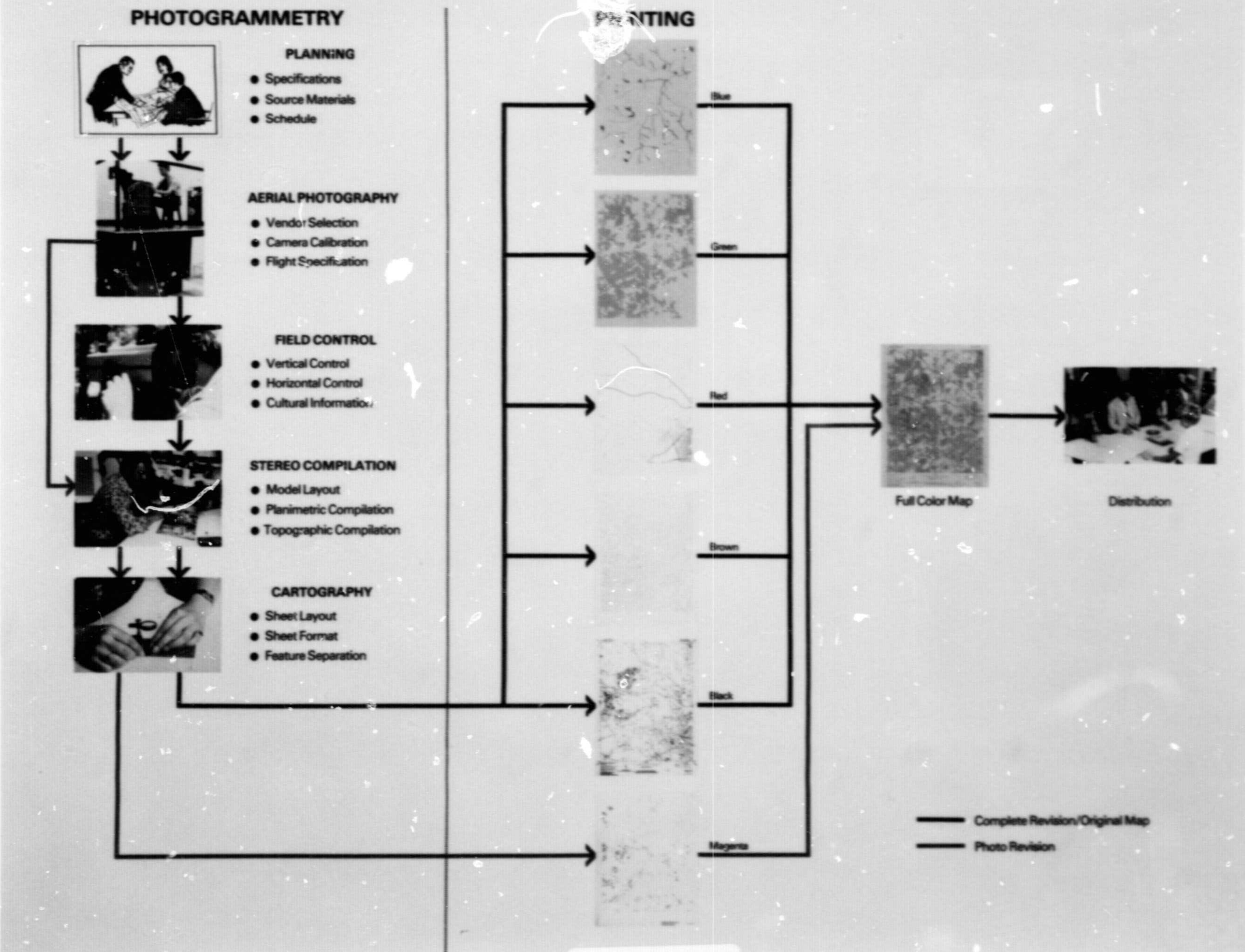
U.S.G.S. CHART PRODUCTION PROCESS



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technology for mapping ignore the ground segment of the mapping process. Both horizontal and vertical control as well as other information for USGS map sheets is obtained by field teams working from the USGS centers. In addition to horizontal and vertical control, the field team is responsible for collecting additional information such as road network and prominent structure categorization, boundaries, monuments, fence lines, crop lines, drainage features, name information (often by interview) and classification of objects that might be misclassified by photointerpretation, such as wooded wetlands.

The National Geodetic Survey (NGS) maintains a horizontal and vertical control network for the entire United States. These points are extremely accurate but may not be of sufficient density to provide enough control points for a 1:24,000 scale 7.5 minute quad sheet. The field team must extropolate from the NGS points to provide photo control points for the aerial photography. Typically, triangulation is used based on the NGS points.

From the aerial photography and field data stereoplotter are used to generate planimetric and topographic data which is used to layout and compile the maps. The reader is referred to the Appendix for a more detailed description.

3.2 REVISION

The decision to revise a map is based upon inspection of aerial photography and assessment of change from the existing maps. Revisions are classified using the following definitions:

Total Revision: Correcting all deficiencies in planimetric and relief features.

Partial Revision: Correcting specified deficiencies.

Photorevision: Updating to reflect planimetric changes. The revised information is not field checked, and is printed in a distinctive color on the new maps (purple).

A complete description of the process may be found in Appendix A.

3.3 NATIONAL MAPPING ACCURACY STANDARDS

The national mapping accuracy standards currently in use were issued on June 10, 1941 after several years of study and coordination between agencies. In many ways, activities and attitudes with respect to aerial photography in the 1920's and 30's were similar to activities and attitudes now with respect to spaceborne scanner systems. Use of photography in mapping was beginning to become common. Lack of standards and control was beginning to affect the credibility of the industry. A number of committees were convened between 1937 and 1940 which resulted in the current standards. These standards, as applied to 1:24,000 scale maps, are as follows:

Horizontal Accuracy: Not more than 10% of well-defined points tested shall be in error by more than 1/50 of an inch. In general, "well defined" is plottable on the scale of the map within 1/100 inch.

Vertical Accuracy: Not more than 10% of the elevations tested shall be in error by more than 1/2 the contour interval. In checking elevations taken from the map, the apparent vertical error may be decreased by assuming a horizontal displacement within the permissible horizontal error of a map of that scale.

At a scale of 1:24,000, 1/50 inch is 40 ft. Therefore, these standards become: 90% of well defined points will fall within 40 ft. horizontally, and 1/2 the contour interval (CI) + 40 times the tangent of the slope (t). The metric equivalents would be 12.2 meters and 1/2 CI + 12.2 t.

There are currently moves afoot to convert these standards to conform to modern scientific statistical terminology and usage vis a vis standard error or standard deviation. At the scale of 1:24,000, 40 ft at 90% would be approximately 20 ft RMS. The vertical standard error would be 0.3 CI + 24 t to RMS (the 90% to one standard deviation conversion is approximately 1.6 instead of approximately 2, since the vertical error is one dimensional as opposed to the two dimensional circular error of the horizontal case). The metric equivalent would be 6.1 meters RMS horizontally and 0.3 CI + 7.3 t meters RMS vertically. Typical contour intervals on 1:24,000 scale maps vary from 5 ft (1.5m) to 40 ft. (12.2m).

4.0
MAPPING FROM SPACE

This section of the report assesses the performance of the existing spaceborne mapping system and, through extrapolation to future expected performance improvements, the likely performance of future satellite mapping systems. The assessment tool used is a version of the ERIM computer model, which is used operationally to geometrically correct Landsat data. For this project, the model has been incorporated into a computer program which allows interactive substitution of different performance characteristics for specified sensor/platform parameters. This computer program allows parametric analysis of mapping system characteristics to be performed, and permits assessment of overall system performance.

The remainder of this section briefly describes the evolution of the ERIM Landsat model, illustrates the application of the interactive program using the model to the Landsat 1 through 3 systems, and presents the results of application of the program to prospective future satellite systems. The interactive program is included as a FORTRAN source listing in Appendix B.

4.1 LAND REMOTE SENSING SYSTEM MODEL

Over a period of several years, ERIM has been developing nonlinear geometric techniques for use with Landsat data. These nonlinear techniques use a pair of 21 term polynomials to map Landsat data into the desired map projection, correcting spacecraft and sensor distortions in the process. The first technique developed does not use a model, but provides a least squares fit between a series of map control points and equivalent image control points in the Landsat data. A digitizing table is used to digitize features from maps which can be easily recognized and identified in the Landsat data. Typical map control points would be road intersections, points on a shoreline, bends in rivers, etc. The digitized map control points are then stored in a file as latitude and longitude. A preliminary transformation, based upon the location of the Landsat scene center, is generated to describe the map control points in scan line and pixel counts for the Landsat scene to be corrected. The Landsat data containing the map control point is displayed on the ERDC display system, the equivalent point in the image located, and identified to the computer. This is repeated for a relatively large number of points (40-50) scattered throughout the image area to be geometrically corrected. A regression analysis is performed between the map control points and the image control points to generate a mapping transformation to convert the Landsat coordinate system to the desired map projection. The accuracy of the correction is limited by the resolution of the Landsat data, the map accuracies, and the precision with which the image and map control points are located. The mapping polynomials used allow correction using up to fifth order terms, providing considerable flexibility. This flexibility, however, is dangerous in that incorrectly identified map or image control points can considerably distort the mapping transformation. No indication of distortions in the transformation can be provided other than experience in examining the polynomial coefficients for suspicioulsy large terms where only minor corrections are normally performed. This inability to detect "wild shots," or erroneous control points, plus the large number of control point pairs required to properly correct a scene, led to the development of a "model" for the Landsat spacecraft and scanner. The model has been under development for several years. The original model was crude, and was initially intended to allow detection of the worst of the "wild shot" control points. The model has been refined to the point where only a few parameters are defined from ground control points. The model uses the information contained in the header record of the Landsat scene, which includes spacecraft latitude and longitude and spacecraft altitude, pitch, roll, and yaw at several points through the scene.

Parameters which are rigidly defined in the model include:

- Sweep to sweep skew due to earth rotation.
- Sampling delays, and errors due to repeated pixels.
- Variations in scan mirror velocity with scan angle (empirically derived from Landsat 1, 2, and 3).
- Perspective or panoramic distortion.
- Oblateness of the earth.
- Desired map projection.
- Elevation of map control points.

In use, several map control points are digitized. The information derived from the scene header record and the model is used to predict the location of the image control points that pair with the ground control points. The image control points are identified, and a least squares fit of control point pairs is used to refine spacecraft roll, pitch, and yaw, and to calculate roll and pitch rates and accelerations.

Using the model, a relatively small number of control points are required provided their locations are accurately known. If precisely located, 5-6 points only are required even if the satellite is maneuvering (roll and pitch accelerations exist). Typically, even if good quality 1:25,000 scale or larger maps of the area are available, ten or so control points will be used to assure that one or two bad points are not distorting the correction transformations. In many cases, however, large scale maps of the area do not exist. The preferred solution to identification of accurate ground control points is use of doppler positioning receivers, which use the TRANSIT series of satellites for precise location of surface features.

As the geometric correction techniques evolved, so did methods for evaluating the performance of those techniques. It was previously mentioned that the first crude rigid model was developed to detect bad ground control points. This aspect of the rigid model approach has continued to be useful. In addition, subroutines of the model software can be used for testing, and a large scale test grid has been established by ERIM for model evaluation purposes. Two test grids, in fact, have been established in a large area in southeastern Michigan and northern Ohio. Each grid contains over 90 ground control points distributed over the area. One grid covers approximately a 40 x 60 mile area shown in Figure 2. The city in the upper left is Toledo, Ohio and the water is the western end of Lake Erie. The test grid for this sub scene area is more or less evenly distributed over the entire area. A plot program has been developed which displays the location of the test grid ground control points when "played through" the rigid model after the 21 term polynomials have been determined. The plot program generates a series of four plots as shown in Figure 3. Figure 3 is a "correct" plot — that is, the model parameters have been satisfied and the residual errors are as small as they can be made with the model being evaluated. Each point of the test grid has a location which can be defined in Landsat coordinates by line and pixel count in the scene. In the upper left plot of Figure 3, the vertical axis is pixel location in the Landsat scene and the horizontal axis is east-west residual error for each ground control point. The verticle scale is the full Landsat scan line (100 N.M.), the horizontal scale is 200 meters per division. If the ground control point, when "played through" the model, were at the right location east-west, it would fall on the middle vertical line. If it occurred early or late (to the east or west) it would fall on one side or the other. Similarly, on the upper right plot, the vertical axis is pixel location on the scene and the horizontal axis is north-south error for each ground control point. The upper two plots are ground control residual errors with respect to their position along a scan line. Similarly, the lower two plots are errors with respect to line locations of control points. The lower left plot vertical axis is scan line count and the horizontal axis is east-west errors, while the

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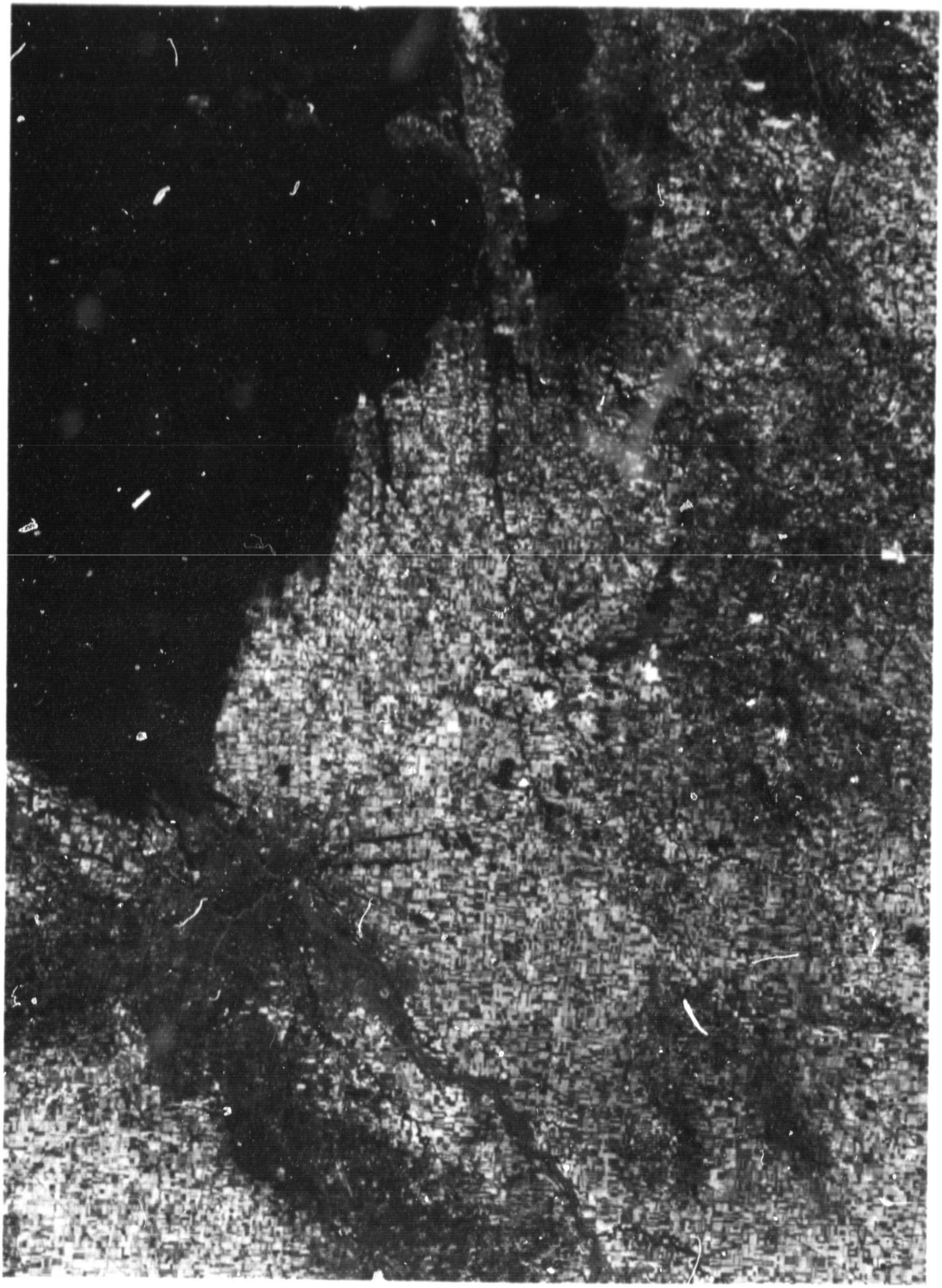

Figure 2. Toledo Area 4C x 60 Mile Test Grid

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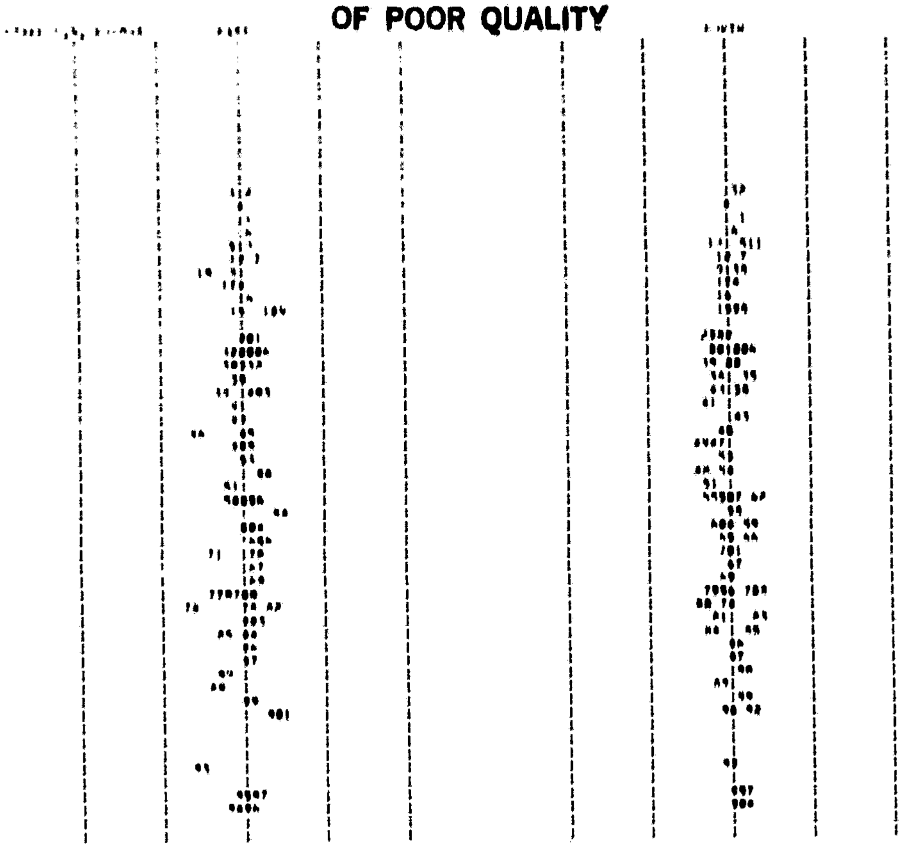

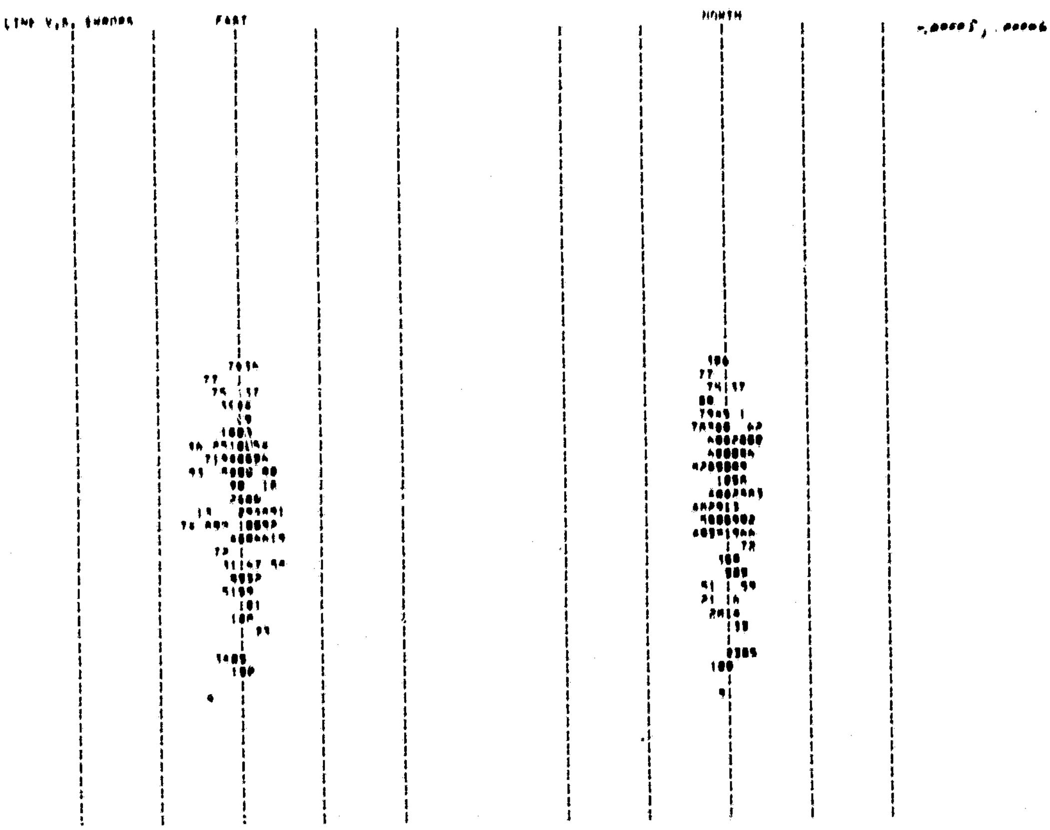

Figure 3

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lower right plot is scan line count versus north-south errors. The scales are again 100 N.M. for the vertical axis and 200 meters per division for the horizontal axis.

It is not necessary to identify individual points to evaluate the plots, but only the distribution of the points. In Figure 3, in all four plots, the points are randomly but evenly distributed about the vertical axis. In Figure 4, an improper mirror velocity profile was used in the model. Notice also the loosening of the distribution of the lower left plot. The two right hand plots are unaffected. For the data set of Figure 3, the east west RMS error is 42 meters and the north-south RMS error is 34 meters. For the data set of Figure 4, the east-west error has increased to 87 meters while the north south error has remained the same. In Figure 5, both a slight roll rate error (lower left plot) and pitch rate error (lower right plot) have been introduced, which cause the respective plots to have slanted distributions. Roll and pitch accelerations cause the lower plots to display nonlinear distributions, while roll or pitch shift the distributions from side to side. Yaw perturbation will affect the pattern of the upper right plot. In each case, a point by point table of residual errors and the east-west and north-south RMS errors are printed out at the top of the printout. Figure 6 shows the beginning of the residual table for the points of Figure 3.

The Landsat model developed by ERIM incorporates, by specification or inference, all of the parameters that affect the ability to generate planimetric maps from space. A number of the parameters apply to any spaceborne remote sensing system, and many apply specifically to the Landsat sensor/spacecraft combination. Examples of the latter category are sampling delays and errors due to repeated pixels, variations in scan mirror velocity with scan angle, and band to band misregistration. However, most of the parameters are such as satellite latitude, longitude and heading, attitude parameters such as roll, pitch and yaw and

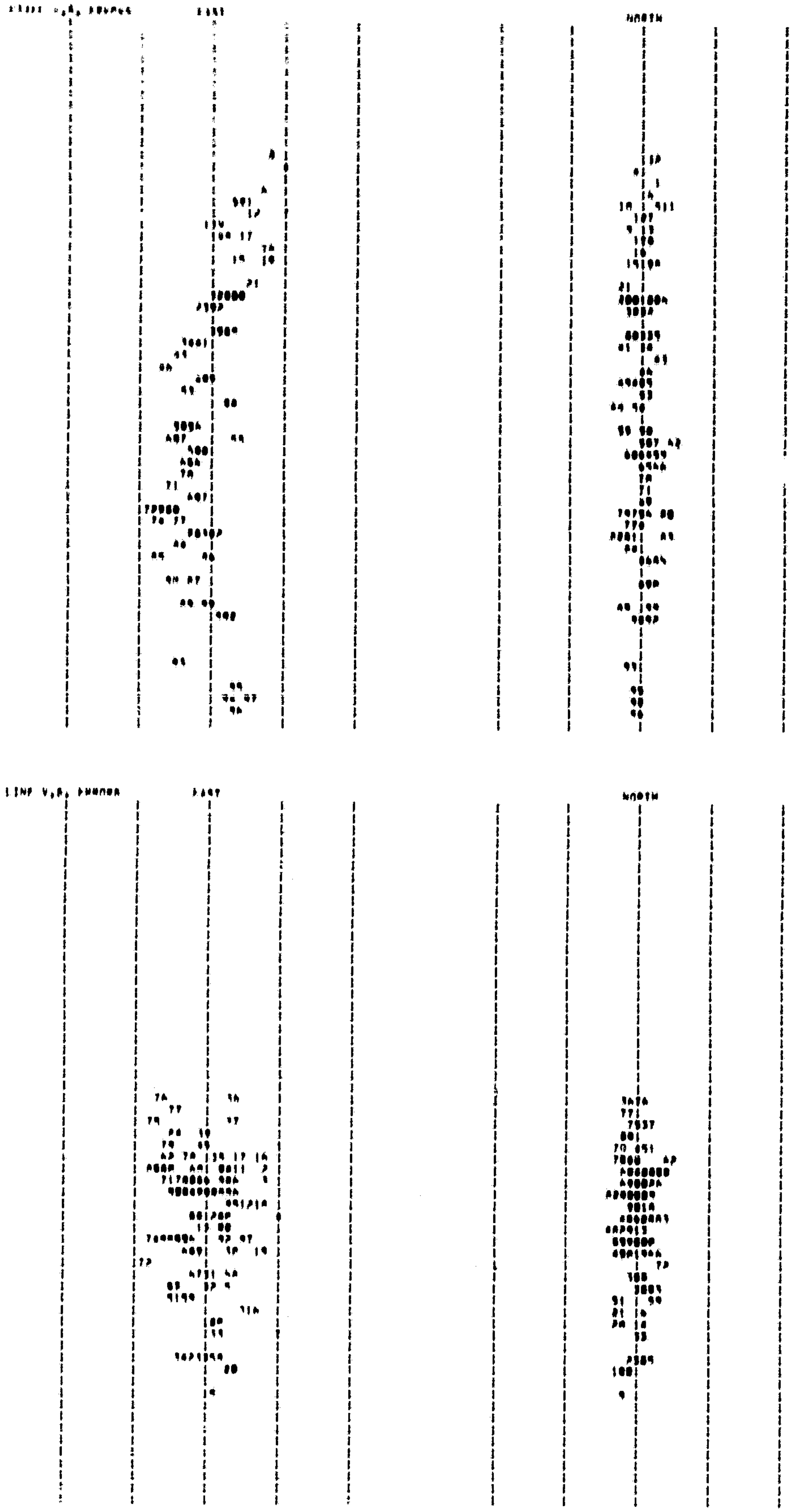

Figure 4

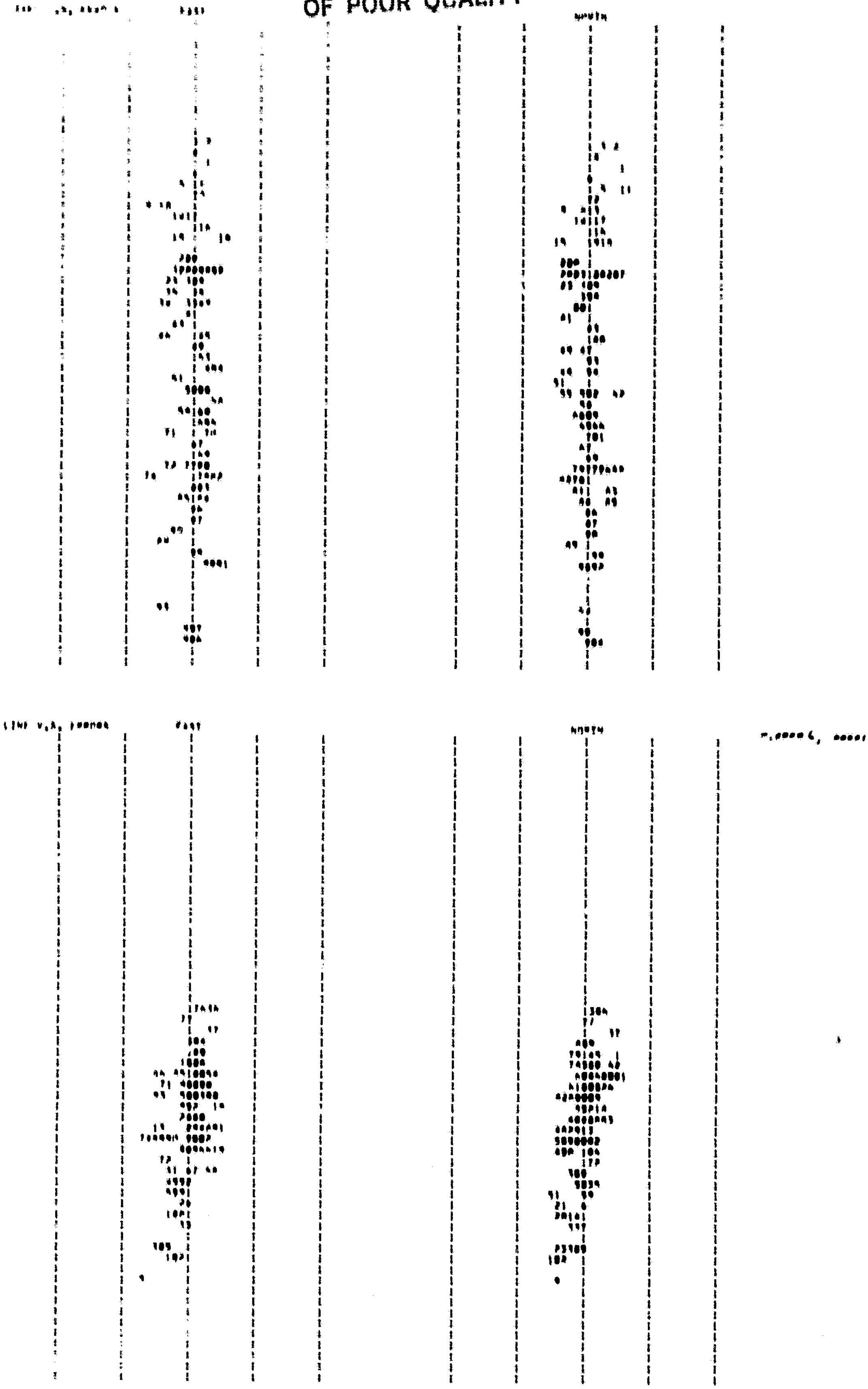

Figure 5

LANDSAT GROUND CONTROL POINTS 14-MAY-79 09147:22

SCENE ID 5021-15271

RMS ERRORS EAST 42. NORTH 34. (METERS)

SPACECRAFT ADJUSTMENTS: EAST 4279.5 NORTH -996.6 YAW

POINT	FILE	WEIGHT	EAST		NORTH	
1	1	1	3.4	0	31.0	1
2	1	1	12.5	0	33.5	1
3	1	1	-22.7	0	2.5	0
4	1	1	-18.1	0	-9.8	0
5	2	1	-21.5	0	39.1	1
6	2	1	19.2	0	13.2	0
7	2	1	37.2	1	31.0	1
8	2	1	-31.6	0	26.8	1
9	2	1	-86.7	-1	-21.2	0
10	2	1	5.6	0	-32.7	0
11	2	1	-11.4	0	62.4	2
12	2	1	-6.8	0	-9.8	0
13	2	1	-91.8	-1	0.4	0
14	2	1	-12.4	0	9.3	0
15	2	1	-3.4	0	-20.0	0
16	2	1	11.4	0	-2.1	0
17	2	1	-36.3	0	-15.3	0
18	2	1	76.0	2	33.1	1
19	2	1	90.6	2	17.4	1
20	2	1	7.9	0	-37.4	0
21	2	1	23.7	1	-40.3	0
22	2	1	16.9	0	-13.2	0
23	2	1	-9.0	0	3.8	0
24	2	1	3.4	0	33.5	1
26	2	1	40.8	1	40.3	1
28	2	1	-9.1	0	22.5	1
29	2	1	1.1	0	-25.5	0
30	2	1	4.5	0	-35.2	0
31	2	1	-27.1	0	-3.4	0
32	2	1	22.6	1	17.0	0

Figure 6

their rates and accelerations, satellite altitude, sensor parameters such as along track and across track sampling interval and field of view, and general mapping parameters such as the figure of the earth, map projections, terrain elevation, etc.

The ERIM Landsat model has been designed to permit precise geometric correction of Landsat data if all the parameters in the model are precisely known. Control points (map or image) are used only to refine not precisely known parameters enough to provide the accuracy of correction desired. If all of the parameters are known to a sufficient degree of precision, then the model can be used to precisely correct Landsat data into planimetric map form. A number of additional outputs from the ERIM computer programs are available. One such output is a listing of the control points used, the residual errors for each control point, after correction, in meters east-west and meters north-south, and the root mean square error of all the control points used.

A sample of such a printout was shown in Figure 6. Other outputs, such as those shown in Figures 3 through 5, are plots obtained by running the control points through the "model" to obtain point by point residual plots.

The software for some of these programs, and a generalized adaptation of the ERIM Landsat model, were combined into a new program which permits the assessment of the expected performance of a postulated cartographic mapping system. A description of this interactive program and a Fortran source listing is included in Appendix B. An example of a printout of the results of the program is shown in Table 1. In this table, the parameters have been selected to represent the Landsat 3 MSS, and the table will be used to describe the results of the computer program.

The top half of the table lists the parameters included in the model, the value of the parameter in appropriate units, and the uncertainty associated with the value in the same units. Throughout the

TABLE 1
Cartographic Model Printout
Landsat 3 - 1 MSS Parameters

PARAMETER	VALUE	UNCERTAINTY
1 LAT	41.6700	0.000057
2 LONG	83.3200	0.000076
3 ALT	997.0000	0.200000
4 HDG	180.0000	0.000000
5 PITCH	0.0000	0.001320
6 ROLL	0.0000	0.000940
7 TILT	0.0000	0.000000
8 SCAN	5.7000	0.001000
9 ELEV	0.1750	0.010000
10 ATSI	79.0000	0.000000
11 CTSI	57.0000	0.000000

PARAMETER	EAST	NORTH
1 LAT	0.1	6.3
2 LONG	6.3	0.0
3 ALT	20.0	0.2
5 PITCH	0.3	23.0
6 ROLL	16.5	0.2
8 SCAN	17.6	0.2
9 ELEV	1.0	0.0
10 ATSI	0.3	22.9
11 CTSI	16.6	0.2

RMS ERRORS	EAST	NORTH	RADIAL
	36.0	33.1	48.9

study, it was assumed that ground control information would be available in the form of control points. Thus, many of the sources of error depend only upon the uncertainty in the knowledge of the parameter, not the value of the parameter itself. In other cases, the value of the parameter is a multiplier for the error. The parameters and the values for the parameter and uncertainties used in Table 1 will be explained as follows.

The units of latitude and longitude 1 and 2, are degrees. The values are immaterial, in that absolute errors would be eliminated by map control. The values shown are latitude and longitude of the center of the ERIM test grid. The uncertainties illustrated are those of the maps used. It is assumed that 1:24,000 scale maps are used, and the errors are the equivalent of map errors at that scale (6.3 M RMS). The altitude parameter is that of Landsat 3, and the altitude uncertainty is our best estimate of the uncertainty in satellite ephemeris. There is no error assigned to heading (yaw). The pitch and roll uncertainties are the RMS sampling errors associated with the selection of image control points, and are the same as the errors due to the data sampling (23 meters and 16.7 meters, corresponding to the 79 x 57 meter sampling interval). It should be noted that for Landsat 3, pitch, yaw and roll information are very poor, and the major use of the control point information is to refine satellite roll, pitch, yaw, and pitch and roll rates and accelerations. For this reason, the image control points must be considered randomly located with respect to the Landsat pixels, and the errors associated with the Landsat sampling must be assigned to pitch, roll and yaw. If these parameters were more precisely defined, then the errors associated with pitch, roll and yaw would be the lesser of either the attitude uncertainties or the sampling errors. The scan angle used is that of the Landsat 3 MSS, and the uncertainty is our best estimate of undefined mirror motion during scan. The elevation of 175 meters is that of Toledo, Ohio (the center of the ERIM test grid) and the associated 10 meter uncertainty was arbitrarily selected. The along track and cross track sampling intervals are those of the Landsat 3 MSS.

The bottom half of the table lists the RMS errors (east-west and north-south) associated with each parameter, the RSS of all east-west and north-south errors, and the RSS of the aggregate errors. All units are meters.

The errors shown as the aggregate errors are typical of those currently being achieved at ERIM using the Landsat model on typical Landsat data. Listed below are residual errors from three Landsat scenes over the Toledo, Ohio path/row, together with the final residuals from Table 1:

		E-W	N-S	Total
Scene	1111-11522	30.5	36.6	47.6
Scene	5021-15271	41.9	36.0	55.2
Scene	2189-15352	66.9	43.2	79.6
Cartographic Model		36.0	33.1	48.9

It should be noted that two of the three actual scenes listed above had satellite attitude accelerations in progress, with the third scene accelerations errors being 700M P-P roll and 400M P-P pitch. The model was only being allowed second order terms to correct for accelerations in generating a fit between satellite attitude and control points. Bearing in mind this constraint, the Cartographic Model simulation yields errors very similar to those encountered with actual Landsat data.

4.2 SENSOR/PLATFORM PARAMETER ASSUMPTIONS

The orbit and performance of the Landsat-D platform was assumed typical of the state of the art during the time frame of the study. These parameters are as follows:

Spacecraft altitude: 705 kilometers, uncertainty of 40 meters RMS using GPS (Global Positioning System)

Spacecraft attitude accuracy: 0.01 degrees, roll, pitch, and yaw, 10^{-6} degrees/second rate

Sensor swath width: 185 kilometers (±7.5° scan angle)

With these basic assumptions in mind, the likely performance of the Landsat-D MSS was assessed assuming the scanner performed essentially as the MSS on board Landsats 1 thru 3 — that is, uncertainties were neither greater nor less except as modified by the above cited parameters. The next assumption added was replacement of the Landsat D MSS with an equivalent performance linear detector array pushbroom scanner (eliminating mirror position uncertainty). Further assumptions were then made concerning ground control accuracy and sensor sampling intervals, knowledge of satellite exphemeris, and knowledge of terrain elevation variations. Sequential imposition of these assumptions led to steady improvement in the expected performance of the satellite system as a planimetric mapping device. No assumptions were made concerning perturbation of the satellite by movement of other systems on the spacecraft. No assumptions were made concerning errors in the geodetic control at the surface of the earth. It was assumed that through use of doppler receivers or a similar approach, location of points on the surface of the earth could be specified to an accuracy of one meter or less.

The major assumption made that does not seem to appear in similar studies is the availability of ground control information to assist in error reduction.

4.3 SYSTEM PERFORMANCE ASSESSMENT

If it is assumed that ground control information is available, dramatic improvements in planimetric mapping accuracies achievable from orbital systems can be made with modest changes in spaceborne system parameters. The cartographic model printout for the present

MSS/platform combination has already been presented, and an approximate error of 49 meters RMS was predicted. Table 2 presents the changes in performance expected for the Landsat D MSS. The changes made were primarily increased accuracy for satellite altitude and attitude. The attitude uncertainties used were worst case, in that the drift of 10^{-6} degrees per second was multiplied by the framing time to get 24×10^{-6} degrees. After the changes, the major errors are associated with the mirror velocity uncertainty and sampling errors. The mirror uncertainty could be eliminated by replacing the MSS with an equivalent performance multilinear array scanner, yielding the results of Table 3. The 30 meter RSS errors are now dominated by uncertainties due to the large sampling intervals. The improvement obtained by adopting a 10 meter along and cross track sampling interval is shown in Table 4. With only this change, the overall errors drop to slightly over 11 meters. The errors in the maps being used for ground control, and the uncertainties in satellite altitude are now the dominant factors. If it is assumed that the Global Positioning System performance will improve from the presently quoted 40 meters to the anticipated 10 meters when all GPS satellites are deployed, and Geoscievers (doppler receivers using the TRANSIT satellites) are used for ground control, then errors of 6.1 meters can be achieved, as shown in Table 5. The results of these five cases are summarized in Table 6. All of the assumptions which have been described are documented as within either the present state of the art, or achievable within the time frame of the study period. The only unsupported assumption that has been made is that terrain elevation is known within 10 meters RMS.

4.4 TOPOGRAPHIC MAPPING USING SATELLITE DATA

The only unsupported assumption in the parametric analysis of the previous paragraphs was that terrain relief information to an accuracy of 10 meters RMS would be available. With such an assumption, planimetric maps to National Mapping Accuracy standards could be generated.

TABLE 2

Cartographic Model Printout Landsat D MSS Parameters

PARAMETER		VALUE	UNCERTAINTY
1	LAT	41.6700	0.000057
2	LONG	83.3200	0.000076
3	ALT	705.0000	0.040000
4	HDG	180.0000	0.000024
5	PITCH	0.0000	0.000024
6	ROLL	0.0000	0.000024
7	TILT	0.0000	0.000000
8	SCAN	7.5000	0.001000
9	ELEV	0.1750	0.010000
10	ATSI	79.0000	0.000000
11	CTSI	57.0000	0.000000

PARAMETER		EAST	NORTH
1	LAT	0.1	6.3
2	LONG	6.3	0.0
3	ALT	5.3	0.0
4	HDG	0.0	0.0
5	PITCH	0.0	0.3
6	ROLL	0.3	0.0
8	SCAN	12.5	0.2
9	ELEV	1.3	0.0
10	ATSI	0.3	22.9
11	CTSI	16.8	0.2

RMS ERRORS	EAST	NORTH	RADIAL
	22.5	23.7	32.7

TABLE 3
Cartographic Model Printout
Landsat D System
79 x 57 Meter Multilinear Array (MLA)

PARAMETER		VALUE	UNCERTAINTY
1	LAT	41.6700	0.000057
2	LONG	83.3200	0.000076
3	ALT	705.0000	0.040000
4	HDG	180.0000	0.000024
5	PITCH	0.0000	0.000024
6	ROLL	0.0000	0.000024
7	TILT	0.0000	0.000000
8	SCAN	7.5000	0.000000
9	ELEV	0.1750	0.010000
10	ATSI	79.0000	0.000000
11	CTSI	57.0000	0.000000

PARAMETER		EAST	NORTH
1	LAT	0.1	6.3
2	LONG	6.3	0.0
3	ALT	5.3	0.0
4	HDG	0.0	0.0
5	PITCH	0.0	0.3
6	ROLL	0.3	0.0
9	ELEV	1.3	0.0
10	ATSI	0.3	22.9
11	CTSI	16.8	0.2

RMS ERRORS	EAST	NORTH	RADIAL
	18.7	23.7	30.2

TABLE 4

Cartographic Model Printout

Landsat D System

10 x 10 Meter MLA

PARAMETER		VALUE	UNCERTAINTY
1	LAT	41.6700	0.000057
2	LONG	83.3200	0.000076
3	ALT	705.0000	0.040000
4	HDG	180.0000	0.000024
5	PITCH	0.0000	0.000024
6	ROLL	0.0000	0.000024
7	TILT	0.0000	0.000000
8	SCAN	7.5000	0.000000
9	ELEV	0.1750	0.010000
10	ATSI	10.0000	0.000000
11	CTSI	10.0000	0.000000

PARAMETER		EAST	NORTH
1	LAT	0.1	6.3
2	LONG	6.3	0.0
3	ALT	5.3	0.0
4	HDG	0.0	0.0
5	PITCH	0.0	0.3
6	ROLL	0.3	0.0
9	ELEV	1.3	0.0
10	ATSI	0.0	2.9
11	CTSI	2.9	0.0

RMS ERRORS	EAST	NORTH	RADIAL
	8.8	7.0	11.3

TABLE 5

Landsat D System

10 x 10 Meter MLA

10 Meter Orbital Uncertainty

Doppler Receiver Ground Control

PARAMETER		VALUE	UNCERTAINTY
1	LAT	41.6700	0.000026
2	LONG	83.3200	0.000035
3	ALT	705.0000	0.010000
4	HDG	180.0000	0.000024
5	PITCH	0.0000	0.000024
6	ROLL	0.0000	0.000024
7	TILT	0.0000	0.000000
8	SCAN	7.5000	0.000000
9	ELEV	0.1750	0.010000
10	ATSI	10.0000	0.000000
11	CTSI	10.0000	0.000000

PARAMETER		EAST	NORTH
1	LAT	0.0	2.9
2	LONG	2.9	0.0
3	ALT	1.3	0.0
4	HDG	0.0	0.0
5	PITCH	0.0	0.3
6	ROLL	0.3	0.0
9	ELEV	1.3	0.0
10	ATSI	0.0	2.9
11	CTSI	2.9	0.0

RMS ERRORS	EAST	NORTH	RADIAL
	4.5	4.1	6.1

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TABLE 6

Summary Table

Performance Versus Parameter Variations

	East	North	Radial
1. Using Landsat 1 - 3 Parameters	36.0	33.0	48.9
2. MSS on Landsat D	22.5	23.7	32.7
3. MLA and Landsat D (57 x 79 meter sampling)	18.7	23.7	30.2
4. MLA, Landsat D platform, 10 meter resolution and resampling	8.8	7.0	11.3
5. MLA, 10 meter resolution and resampling, 10 meter GPS, 1 meter latitude and longitude	4.5	4.1	6.1

Neither the manpower nor time to perform an independent study of stereographic satellite designs was available, but existing reports from other organizations could be analyzed. The most fruitfull of these reports was published by ITEK in February 1981 describing work preformed under contract 14-08-0001-18556 for USGS to investigate an Automated Mapping Satellite System. Without evaulating the design presented in detail, the stated ability to generate topographic data to a 10 meter RMS accuracy appeared credible. This accuracy is sufficient to permit planimetric mapping to a horizontal accuracy of 6.1 meters, and was used in this study.

Examination of a number of USGS 7.5 minute quad maps, produced at a scale of 1:24,000, concluded that contour intervals varied from 5 feet (1.5 meters) to 40 feet (12.2 meters) depending upon the degree of terrain relief. To meet the requirement to provide 1/2 contour interval accuracy 90% of the time would require an elevation accuracy of 0.5 meters RMS. This appears beyond the state of the art for the near future under any reasonable set of design assumptions. This aspect of the tradeoff study was abandoned.

5.0 CONCLUSIONS

Nearly all uncertainties associated with mapping from space can be attributed to the sensor/platform combination if ground control assistance can be used; this is especially true with the advances taking place in digital processing and mapping techniques.

Assuming that precise (1 meter uncertainty in X, Y, and Z) ground control is available, and terrain elevation information to an accuracy of 10 meters RMS or better is available, existing and prospective spaceborne state of the art will permit planimetric mapping to National Mapping standards at scales of 1:24,000 or larger. Some redefinitions in the standards would have to be made, such as:

- o Approving "one standard deviation" equivalent to the current 90% confidence standards. This would require incorporation of wording such as "within 1/50 inch 90% of the time or an RMS accuracy of 1/100 inch".
- o Approving "one standard deviation" equivalent to the current "well defined points" stipulation. The current definition of well defined point requires that it be plottable within 1/100 inch at the scale of map. At 1:24,000, this would require resolving a 6 meter object with a 10 meter IFOV. However, a 10 meter scanner could locate a network of points to a 3 meter RMS accuracy, which would meet the intent of the requirement.

Neither of these changes are degradation of the standard, but are restatements in other terms.

The requirement for 10 meter elevation information could be obtained either from digital terrain models or from stereo satellite information. However, it does not appear that satellite sensors can meet accuracy standards for topographic mapping at 1:24,000 scale.

The fact that 1:24,000 scale topographic standards cannot be achieved from space does not mean that spaceborne sensors cannot contribute to the U.S. mapping program. Bear in mind that the entire United States will be mapped at a scale of 1:24,000 by 1988. Consequently, all subsequent mapping efforts will be revisions, which can be made using the spaceborne sensors unless there have been radical changes in topography. Therefore, it is likely that over 95% of all mapping requirements could be met with spaceborne sensors after 1990. Further, spaceborne sensors could also be used to detect which areas had been changed to the extent that new aerial photography is required.

APPENDIX A

ΣERIM

USGS CHART PRODUCTION
Process for 1:24,000 Charts

Purpose

The purpose of this report is to define in a step-by-step manner the chart production process currently being used by the United States Geological Survey (USGS). The process will be described in the map-making process section with separate parts devoted to each step in the preparation of 1:24,000 quad maps and accuracy standards required by USGS. Finally, a flowchart will be presented summarizing the steps involved in producing a USGS 1:24,000 Quad sheet.

Mapmaking Process

Mapmaking at USGS has been and continues to be a constantly changing process due to variations in types of maps required by the user community and advances in the technology of map production. As shown in Figure A-1, the types of maps produced by USGS has changed drastically from its birth in 1880 to the present day. Almost immediately after USGS was formed, production began on a large scale series of maps (1:62,500) to meet the needs of agriculturalists, mining eningeers, and timbermen. Nearly a 100 years later, this series of maps is still the only map available for many areas of the United States. During the 1950's, continuing requirements for greater detail in maps resulted in a shift to the 1:24,000 quad map series. This is the prevailing map scale used in the United States today. The USGS is currently undergoing a shift to the metric system and all mapping accomplished in the future will be at a 1:25,000 scale. Currently the entire state of Massachusetts is being mapped at this new scale, creating many problems along boundaries between 1:25,000 and 1:24,000 scale quads. The Survey is

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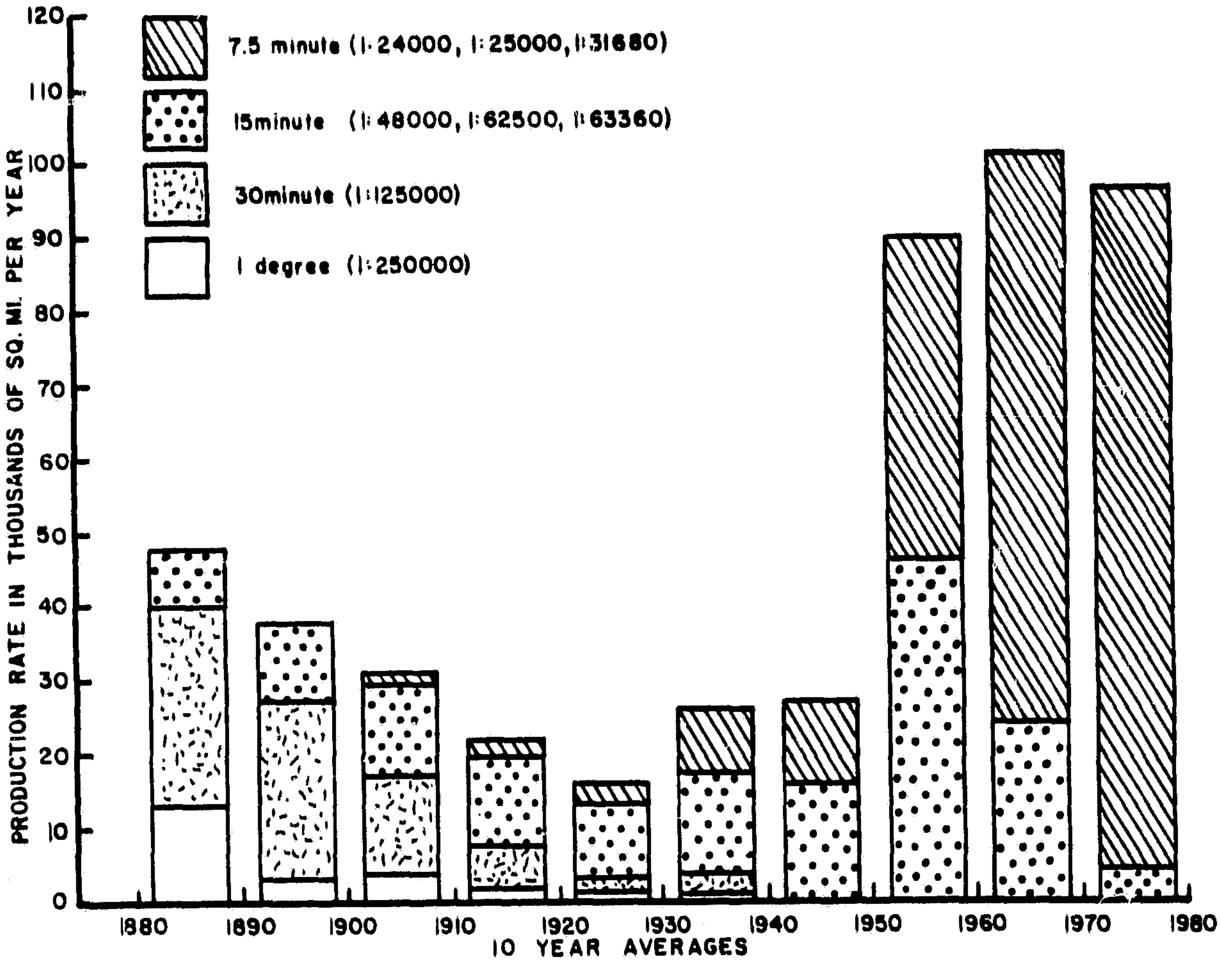


Figure 1. USGS Map Scales and Production Rates Shown as 10 year Averages, 1880 - 1980, (adopted from Maps For America, Reference 8).

also producing, due to the extreme pressure from the public and private sector, a provisional series of 1:24,000 quads for areas not mapped at 1:24,000. These quads are not as accurate as the normal charts and contain much hand editing, but are available quickly to meet the needs of the user.

Technology in map productiton has also changed drastically over the years. Advances in aerial photography and stereo compilation techniques will allow completion of the 1:24,000 series of quad maps by 1988. Figure A-1 shows clearly the major jump in production in the 1950's, due to advances in technology and introduction of the new series.

In addition to original mapping, the survey also maintains a revision program to correct deficiencies in maps produced at an earlier time. The survey classifies these revisions using the following definitions:

Revision: Updating, improving, and correcting map content for publication in the same series.

Total revision: Correcting all deficiencies in planimetry and relief features, including improvement in vertical and horizontal accuracy to result in a map meeting current specifications.

Partial revision. Correcting specified map deficiencies. The revised data appear on the published map in conventional colors.

Photorevision: Updating maps using aerial photographs and other available sources to reflect planimetric changes which have occurred since the date of the latest existing map. The revised information is not field checked and is printed in a distinctive color on the new map.

Photoinspection: Comparing the latest published map to recent aerial photographs to determine both the need for revision and the extent of the changes.

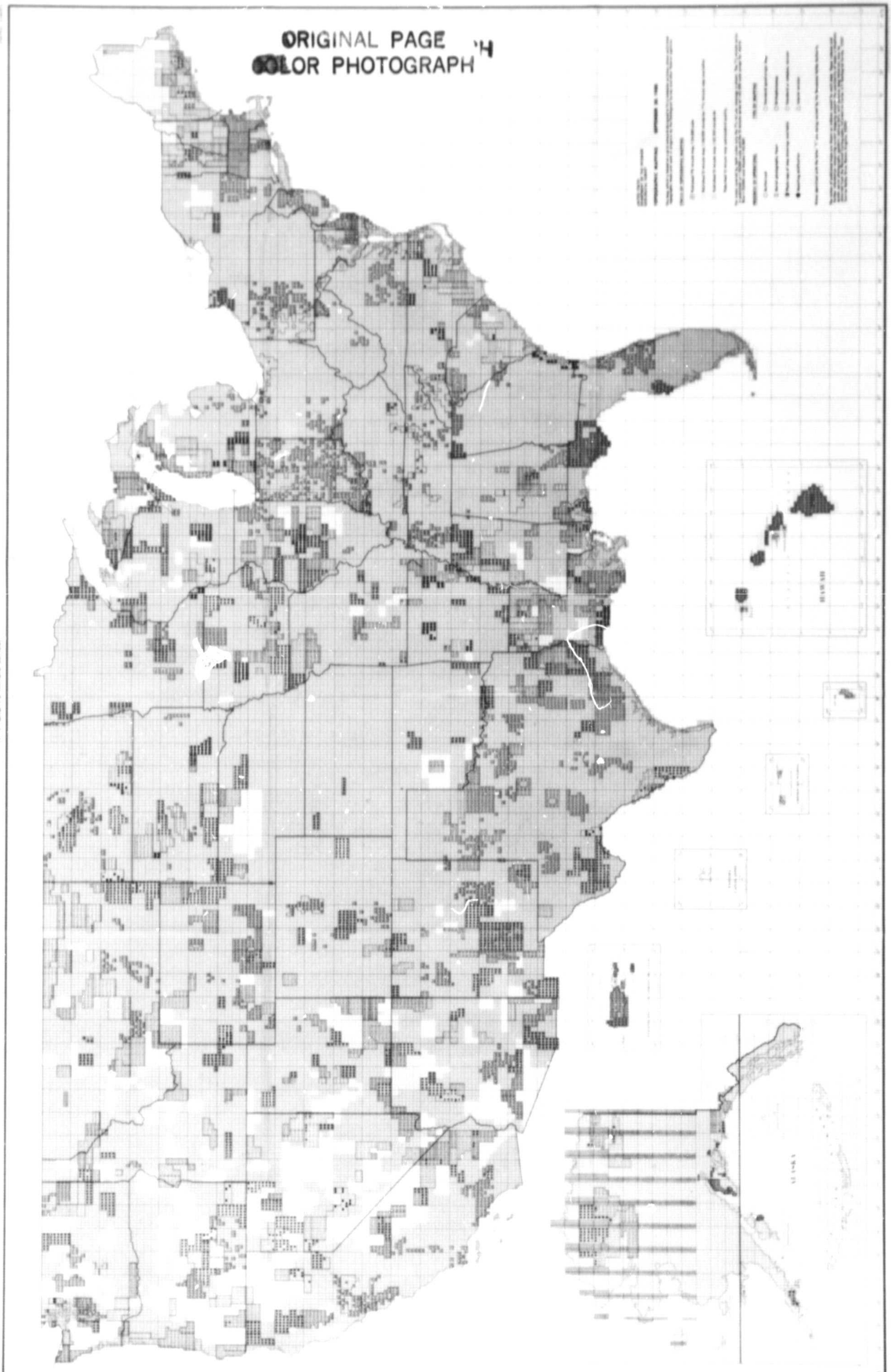
Therefore, one can readily see that mapmaking is a very dynamic process that requires development of new techniques and constantly changing production requirements at USGS.

Planning

Planning is probably the most important step in the production of 1:24,000 quad sheets and is accomplished at every stage of the production process. This section will describe only the planning required as an initial step.

The United States (excluding Alaska) contains approximately 54,000 quad sheets. These sheets were placed into full production in the 1950's and are scheduled for completion in 1988. The four USGS regional mapping centers (Attachment I) are authorized 1,000 new quad sheets each year. It requires three and one-half to five years from the planning stage to the printing of a new quad sheet. Approximately 4,000 of the sheets completed require resurvey at the present time. The survey currently authorizes 50 - 100 complete revisions and 1,300 - 1,500 limited revisions per year. In addition to the 1:24,000 and 1:25,000 quad map series, the survey is responsible for several other map sheet series. These rather impressive statistics clearly point out the need for detailed planning at every step of the operation.

With the large quantity of maps that must be produced by USGS each year, many state and federal agencies have a vested interest in which quads are placed into the production process. Figure A-2 shows the current status of 1:24,000 quad sheets in the United States. Note that most of the United States is either completed or in some phase of the production process. Each March the USGS canvasses approximately thirty State and Federal agencies to determine their priorities for maps to be published by USGS. A weighting system for the agencies is used and computer analysis techniques applied to develop a numerical presentation of the priorities for quad sheet production. Using these computer



TOPOGRAPHIC MAPPING
STATUS AND PROGRESS OF OPERATIONS
7½ and 15-minute series

priority listings the planning group then determines the candidate quads that could be placed into production for the year. Since the map priority schemes do not always match the maximum production criteria, the planners then select, based on the numerical presentation and their own judgement, the quads to be placed into production. For example, if a high priority quad falls within the middle of a group of quads that have not been completed, it becomes much more efficient and cost effective to collect the photography and ground control for the entire area and produce the entire block of quads.

Inspection of existing quad maps is accomplished continuously and the following criteria are used to determine when a quad should be updated:

1. Photo Inspection - The National High Altitude survey program, currently in the stage shown in Figure A-3 and scheduled for completion in 1988, will obtain high altitude aerial photography in both Color IR and Black and White of the entire United States. As the photography becomes available, comparison is made with the USGS charts. Certain minimum thresholds of error between existing maps and the aerial photography have been established by USGS that requires a map to be updated (examples of revision criteris is shown in Table A-1). Whenever these thresholds are crossed, the photography is used to photo-revise the map or to select one of the other revision processes.

2. Requests - Many cooperative programs are available between the USGS, federal agencies, and various states, that allow these groups to request revision of specific maps.

3. Age - Many maps were produced at a time when control may not have been as accurate as the control developed today. These maps may require complete revisions simply on the basis of age.

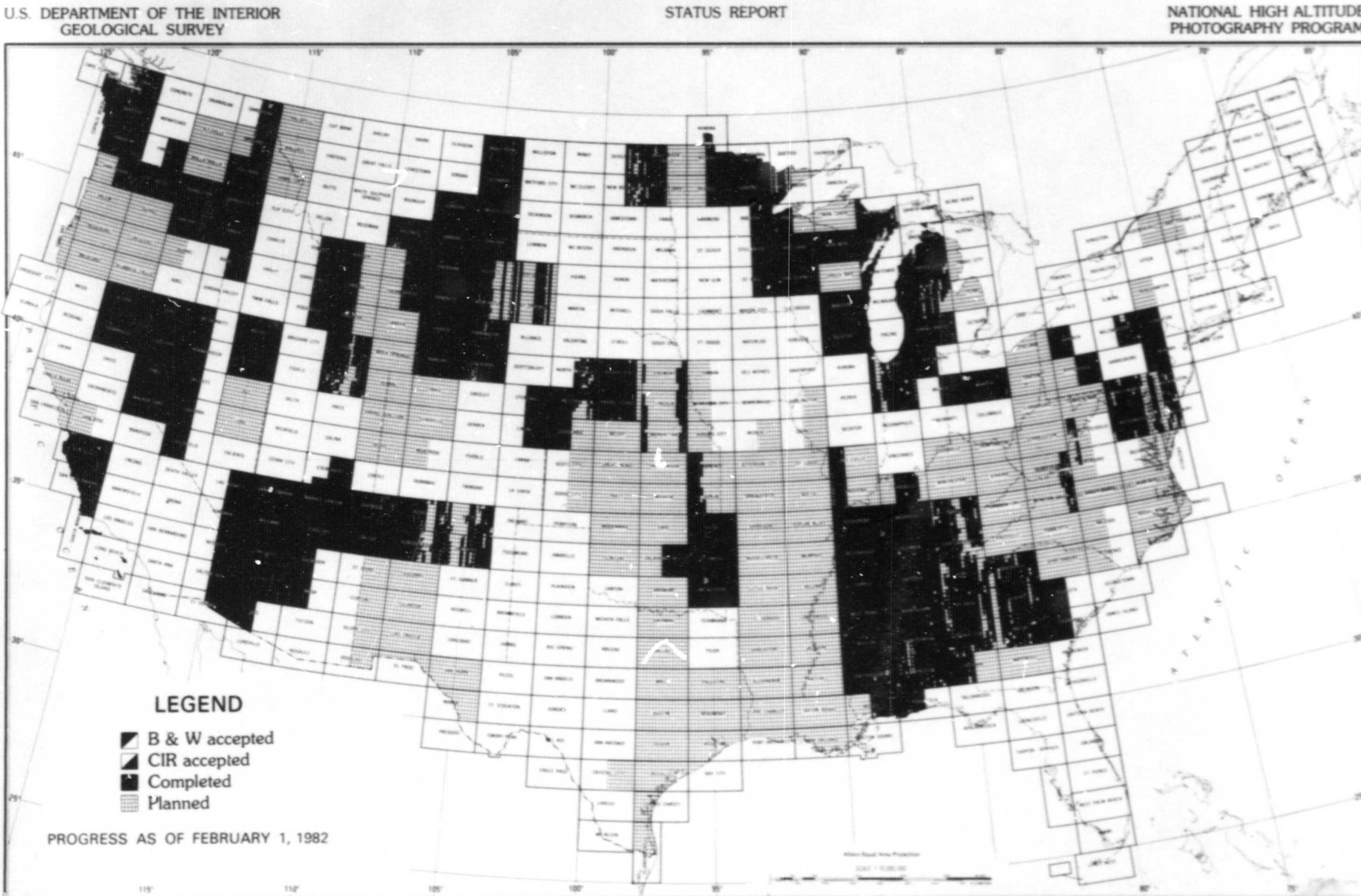


Figure A-3 National High Altitude Survey Program

TABLE A-1 REVISION CRITERIA EXAMPLES

MINOR CHANGES
(3 required)

Feature	Revision Criteria
Stock tanks, private ponds.	Eight per quad with average width 200-300 ft.
Private landing fields, generally not hard surfaced.	One or more, regardless of size.
Large areas, usually with rail or highway access, designated as industrial parks, manufacturing, or commercial areas.	One of more buildings totaling 100,000 ft sq. or more.
Major timber areas or orchards.	Total of 2 mi sq of addition or deletion with no area less than 1 mi sq.
Pipelines, major power transmission lines, ditches.	5 miles per quad with no segment less than 1 mile.

MAJOR CHANGES

Interstate and major highways at least four lanes.	1 mile per quad (or in lesser of amounts if necessary to preserve continuity of the feature through a block of several quadrangles).
Double-line roads symbolized by 40-foot road width.	5 miles per quad with no segment less than 1 mile.
Double line. Single line, perennial	1 mile per quad. 5 miles per quad with no segment less than 1 mile.
Water storage, controlled outlet.	1 mile or more in length and covering at least 0.25 mi sq.
Major landing fields: private, commercial, or military, generally hard surfaced.	New runways, additions, or changes of at least 0.5 mile.

Table A-1 (Cont'd.)

Areas of disturbed earth, active or inactive.	Extensions of mining area or or reclaimed areas of at least 0.25 mi sq.
Areas in and surrounding metropolitan areas.	Subdivision-type pattern of streets and buildings covering at least 0.125 mi sq.
TOTAL REVISION	
All roads, railroads, drainage, coastline, and airport runways and taxiways.	50 miles.
Reservoirs, strip mines, urban-suburban and beaches.	15 mi sq. or 25 percent of land area.

4. Urban areas - Large metropolitian areas are scheduled for update on a five-year cycle. These areas are the most dynamic in terms of change and requires this type of treatment.

Whether it is photo-revision or original mapping, the planning steps in all phases of the production activity is probably the most critical process. A great deal of judgement is required by the planning group to balance requirements and determine revision and production criteria.

Aerial Photography

Even though USGS contracts all aerial photography to outside vendors, they maintain complete control of the data collection mission. This control is accomplished by establishing stringent photographic specifications in the contract with the vendor. The essence of the specifications provides that stereoscopic coverage must be obtained for the project area within the usable limits of the lens system of the plotting instruments on which the photography is to be used. The photographs must be exposed in a camera system manufactured and calibrated to a degree of precision meeting or exceeding that of the stereoplotting equipment. To insure that vendor cameras meet their specifications, the USGS maintains a calibration laboratory at Reston, Virginia. All vendors selected by USGS for mapping are required to have their instruments checked and calibrated at the laboratory. This requirements insures that USGS maintains the consistency and quality that must be obtained for mapping of large areas over many years.

Much of the photography collected for 1:24,000 quad maps is of the quad-centered variety with 6-inch focal length cameras. Since several photographs may be required for complete stereoscopic coverage of the quad, a calibration procedure to insure accurate exposure sequences is a necessity. Equally important in the acquisition of a high quality stereoscopic product is the flight line spacing and altitude of the aircraft which are determined by the scale and contour interval of the map being produced. The USGS assures that flight specifications are met by providing the contractor with detailed flight maps showing beginning and ending of each flight line and the flight altitude above ground or sea level. After the photography is delivered, detailed inspection is made of the finished film to assure flight specifications have been met by the vendor. In addition, the USGS has established specifications for the season the images are to be collected, cloud cover requirements, the time of day the data is to be collected, and minimum criteria for tilting and indexing of the photography.

Control Field Surveys

The National Geodetic Survey (NGS), as a part of the National Ocean Survey (NOS) of the National Oceanic Atmospheric Administration (NOAA), is responsible for maintaining a horizontal and vertical control network for the entire United States. (Figures A-4 and A-5). These points are extremely accurate but are not always of sufficient density for control of 1:24,000 quad sheets and may not be easily located on an aerial photograph. Since horizontal points are marked on the images by the planning group, the field team must extrapolate from the NGS points to obtain the precise location of the photo control point.

Both horizontal and vertical control as well as other information for USGS Quad sheets is obtained by field teams working from the USGS centers. The activity is accomplished on a year-round basis with the teams working in the north in the summer and south in the winter. The teams usually consist of a USGS surveyor and one part-time employee from a local college or university. The teams are supplied with stereo pairs and photo mosaics of the quads. The prints have been marked with suggested locations for horizontal and vertical control points. The field teams must travel to the area of the quad sheets and absolutely locate the horizontal points and measure the elevation of the vertical control

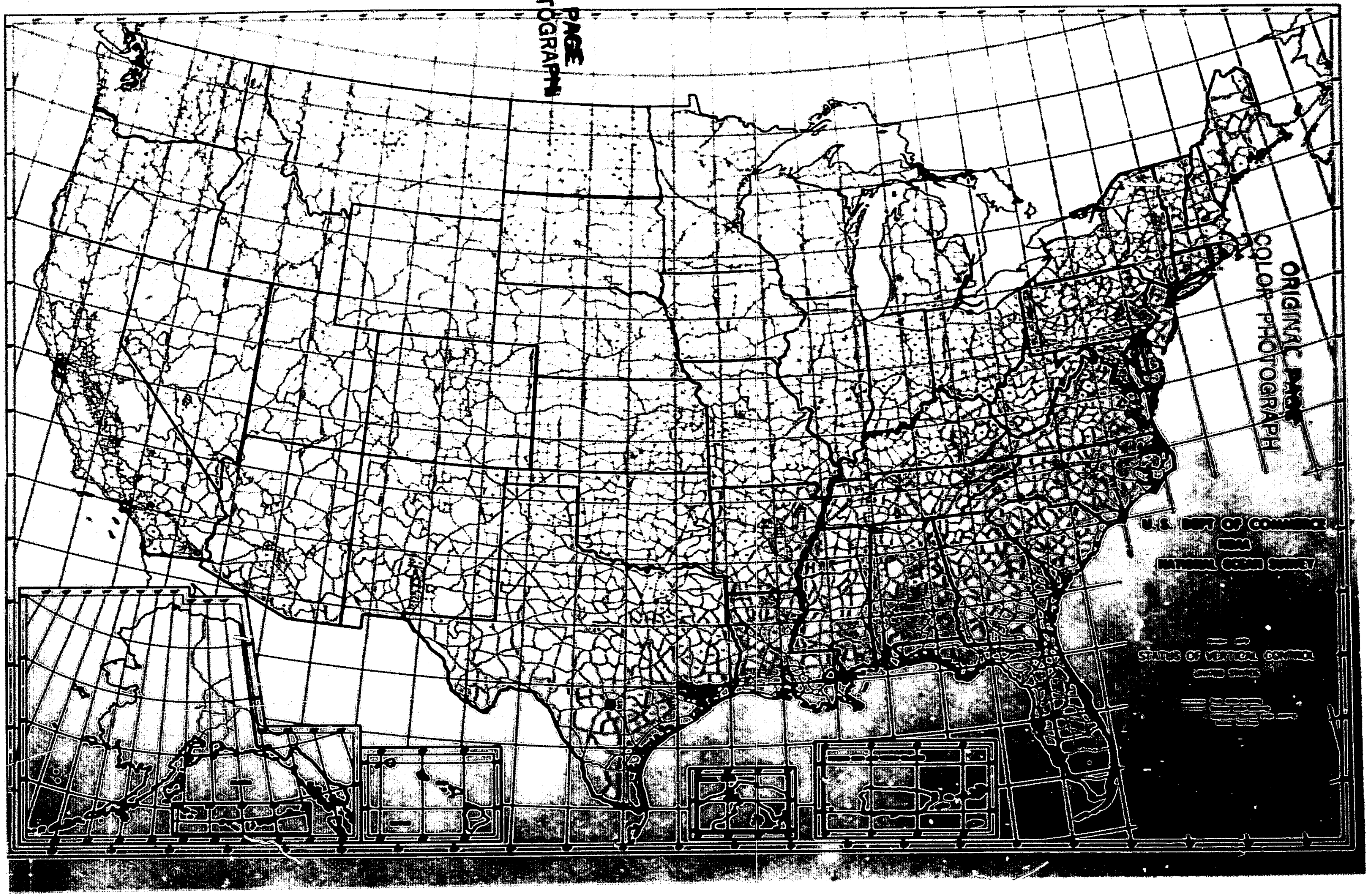


Figure A-4 Status of Vertical Control

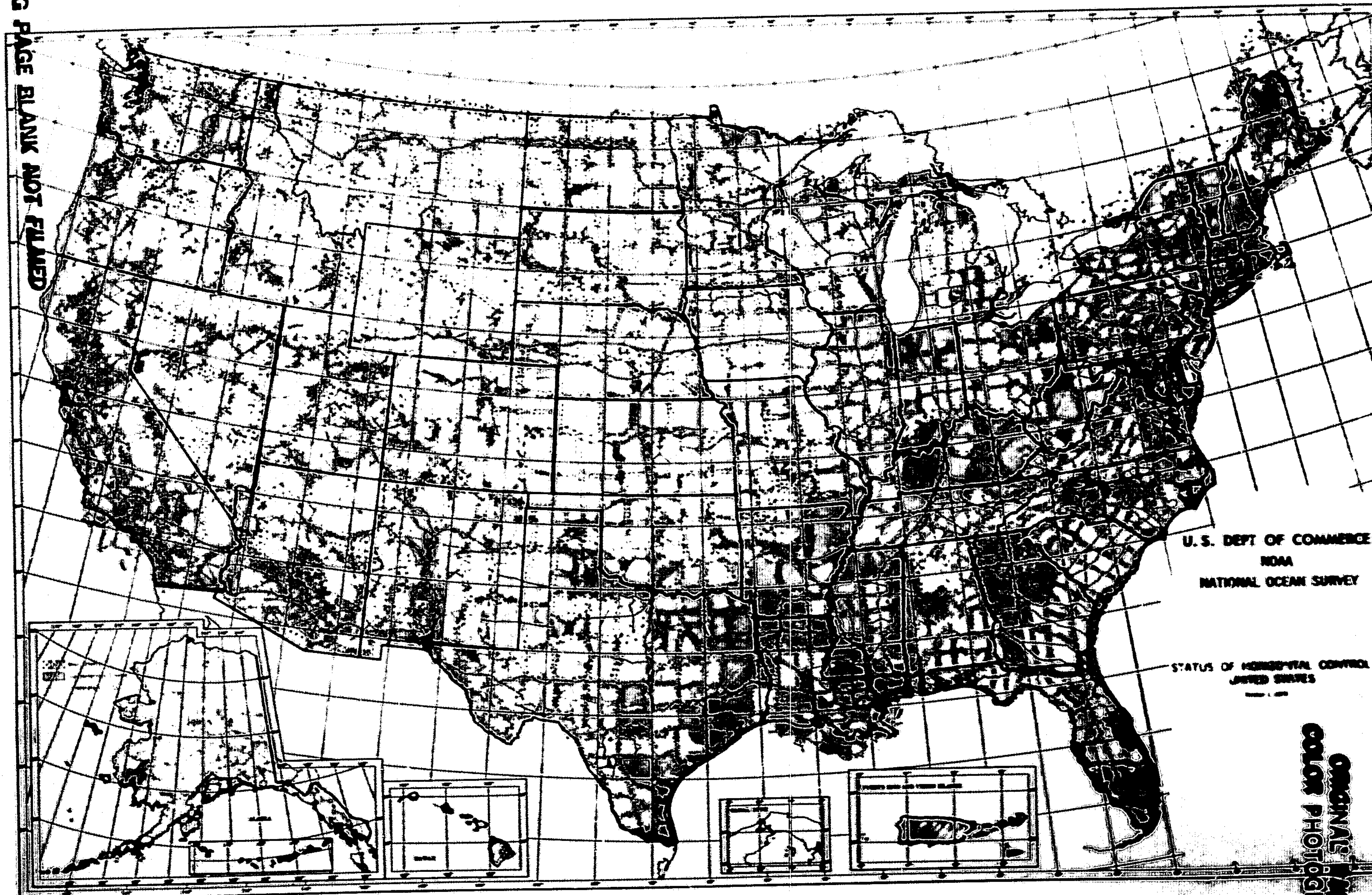


Figure A-5 Status of Horizontal Control

points. These points, whenever possible, are located at 7.5 minute intervals along lines of latitude and longitude, effectively in the corners of 7.5 minute quads or as close as possible to the corners. Various methods of locating these points are used, depending on the ingenuity of the surveyor. Typically though, triangulation is used based on control stations of known location. Regions where verticle control is required are marked on the photographs as squares rather than as points, giving the surveyor some discretion as to where the control may best be located.

In addition to horizontal and verticle control, the field team may be responsible for collecting additional information such as:

- Spot elevations conforming to special accuracy standards are collected to provide more accurate information than may be interpolated from the contours or to supplement the contour information in flat area where contours are widely spaced.
- Road networks are checked and classified according to specified standards.
- Prominent structures are categorized.
- Civil boundaries, monuments, fence, and croplines are also noted on the manuscript.
- Drainage features are categorized and annotated on the photography. The field team is expected to classify all drainage that may contain water by symbols.
- Objects that may be misclassified during stereo compilation, such as wooded wetlands are annotated by the field teams.
- Name information must be collected by the field teams. This often requires research through official records or talking with local residents.

- Areas of special cultural activity, such as industrial mining, public recreation, and historical sites require careful documentation by the field team.

  The field teams are highly trained individuals requiring more than just a background in the use of survey equipment.

Photogrammetric Surveys

This step in the production of quad maps involves using aerotriangulation techniques to extend the field control and then the actual plotting of ground features and contours onto a stable base material for use in the drafting section. The aerotriangulation method uses a monocomparator and the ground control points established in the field to develop supplemental control over the entire photographic model. This supplemental control is accurate enough for most mapping purposes and represents significant cost savings compared to collecting these points in the field. The stereo models are then established by the stereoplotter operators for use in the stereo-plotting device.

Stereoplotters are based on the eye's ability to percieve depth. Just as the eyes percieves depth by focusing on different areas of the object, the stereoplotter achieves depth by focusing one image taken from an aerial camera on one eye and another image of the same area taken by the camera at a different position on the other eye. The difference in perspective produced by stereoscopic viewing creates a mental image of relief or three-dimensional effect. The stereoplotter operator views the model in stereo and using the field measurements for reference traverses contours on the images. These contours are automatically transferred to a plotting device which produces the contour information on stable-base material. USGS uses the Kern PG2 and Wild B8 stereoplotting devices.

For a complete discussion of Photogrammetric surveys, see reference 5, pages 519 - 697.

Cartography/Drafting

The final step in production of the map is the actual layout and compilation of the map data. This entails scribing or inking of various features onto the separates. A quad sheet is usually composed of several separates each representing features to be depicted on the final map. It is also at this step that tick-marks, symbols, credit lines, and other information found around the outside of a 1:24,000 quad are added. These separations are used to prepare the plates used in the printing process. Reference 9 contains a complete list of features found on standard 7.5 minute 1:24,000 quads and other maps series and scales.

Printing

The printing plant at USGS uses a five color process to produce the final map. The feature separates are combined to produce individual color separates for the printing process. For instance, to obtain the black information, several separates representing roads, text, and other information may be combined to produce the color separate. In the same way, separates are combined to produce the other colors (red, blue, etc.) information on the sheet. The separations are then produced as printing plates in the printing plant and printed four maps to a run. Once maps are printed, they are forwarded to the distribution group and sold to the public.

Distribution

The USGS has two main distribution points for 7.5 minute quad maps of the United States. Typically, maps west of the Mississippi are ordered from the:

Branch of Distribution
U.S. Geological Survey
Denver Federal Center
Denver, Colorado 80205

Maps east of the Mississippi, are ordered from:

Branch of Distribution
U.S. Geological Survey
1200 South Eads St.
Arlington, VA 22202

Indexes for obtaining map coverage by state are also available free from the two offices listed. These indexes, Figure A-6, are typically at 1:1,000,000 scale and show available map coverage for an entire state. These indexes also include information on unmapped areas, maps at other scales, and the survey date for each map shown. The reverse side of the index lists information on general maps of the United States, special map series, map reference libraries within the state, and the location of dealers who have over-the-counter sales of USGS maps. Included with each index is an order form (Figure A-7) with a check list that may be used to order any map listed on the index. Map orders with either distribution center will typically take two weeks from placement of order the until the receipt of the maps.

National Map Accuracy Standards (NMAS)

According to NMAS horizontal accuracy standards, not more than 10 percent of points tested on a USGS 1:24,000 scale quadrangle shall be in error by more than 1/50 inch. The points tested are limited to positions that are easily recognized on the ground such as monuments, bench marks, road and rail intersections, corners of large structures, etc. These points are generally plottable on the scale of the map within 1/100 inch. Conversely, features not identifiable on the ground, within close limits are also not to be considered test points. The vertical accuracy standards are such that no more than 10 percent of the eleva-

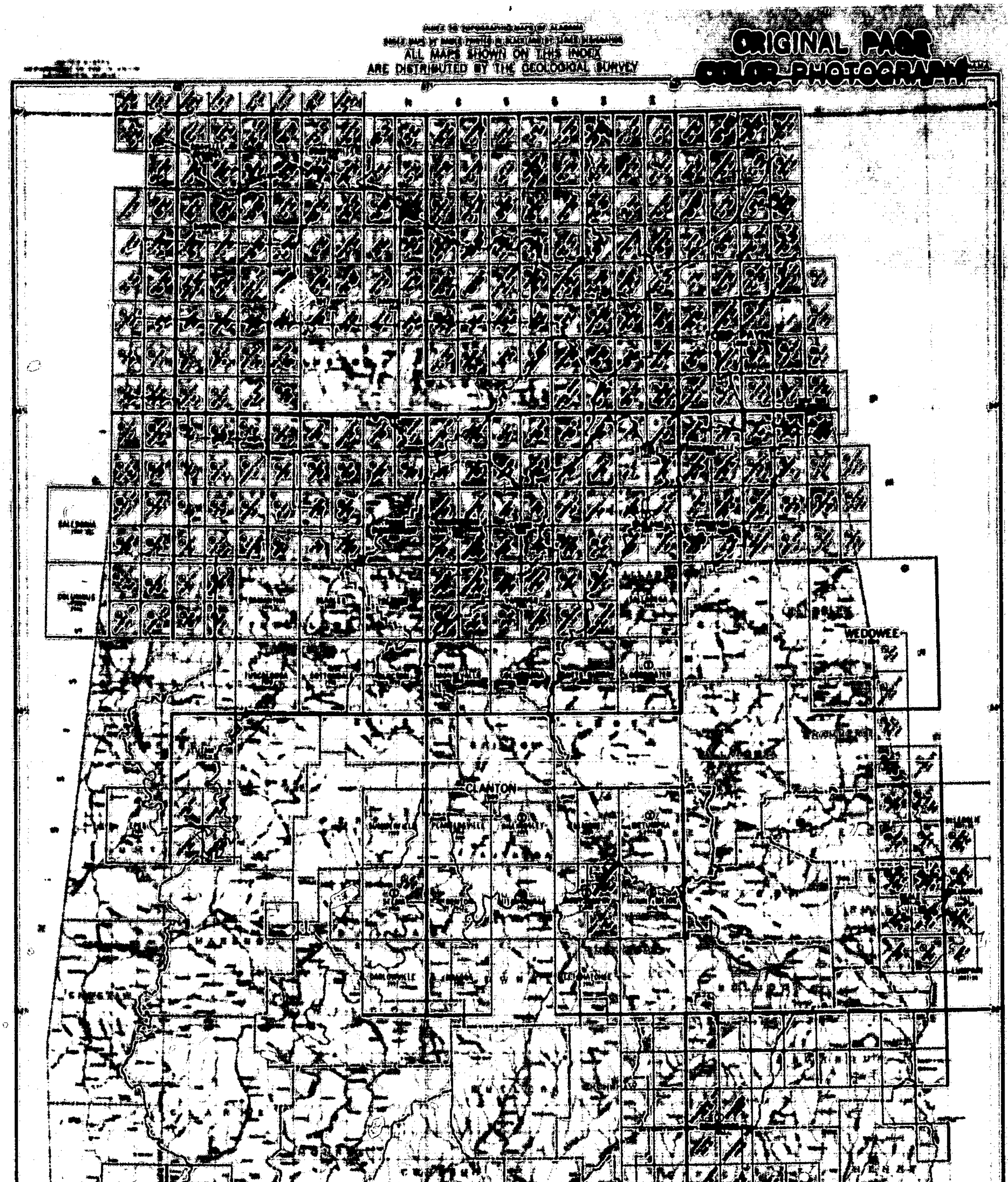


Figure A-6 USGS Quad Index

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ALABAMA

MAP ORDER FORM

Mail this order to:

BRANCH OF DISTRIBUTION, EASTERN REGION
U.S. GEOLOGICAL SURVEY
1200 SOUTH EADS STREET
ARLINGTON, VIRGINIA 22202

FROM: Name ____	Customer Order No.	OFFICE USE DO NOT WRITE IN THIS SPACE
____	Date	
Street Address ____	Total Maps Ordered	
City State Zip Code	Amount Enclosed $____	
PREPAYMENT REQUIRED Remittance payable to U.S. Geological Survey. List prices given include cost of surface transportation.	Check ___ Money Order ___	

DISCOUNT On an order amounting to Three Hundred Dollars or more, a 30% discount is allowed. No other discount is applicable.

SURCHARGE For transmittal of maps outside of the United States (except for Canada and Mexico), a surcharge of 25 percent of the net bill will be added to cover surface transportation. Special service will be charged at full cost of service.

FOR PROMPT, ACCURATE SHIPMENT PLEASE FILL IN MAILING LABEL ON LAST PAGE

MAPS OF THE UNITED STATES. For detailed description see text on Index.

Base Maps

___Map 2-A, scale 1:2,500,000, 2 sheets, land tint background; $3.00 per set.
___Map 2-B, scale 1:2,500,000, 2 sheets, without land tint background; $3.00 per set.
___Map 3-A, scale 1:3,168,000; $1.50.
___Map 5-A, scale 1:5,000,000; $1.25
___Map 5-B, scale 1:5,000,000; $1.25
___Map 5-C, scale 1:5,000,000; $1.25
___Map 6-A, scale 1:6,000,000; $2.00.
___Map 7-A, scale 1:7,000,000; $1.25
___Map 10-A, scale 1:10,000,000; $1.50.
___Map 11-A, scale 1:11,875,000; .50
___Map 16-A, scale 1:16,500,000; .25

Contour Map

___Map 7-B, scale 1:7,000,000; $1.25

Outline Map

___Map 5-D, scale 1:5,000,000; $1.25

Physical Divisions Map

___Map 7-C, scale 1:7,000,000; $1.25

___Conterminous United States NASA ERTS-1, Satellite Image Mosaic, Band 5-Summer. $1.25.
___Conterminous United States NASA ERTS-1, Satellite Image Mosaic, Band 7-Summer. $1.25.

Figure A-7a

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OF POOR QUALITY

___ Chickasaw
___ Childersburg
___ China
___ China Grove
___ Choccolocco
___ Chrysler
___ Claiborne
___ Clairmont Springs
___ Clanton East
___ Clanton West
___ Clarence
___ Clayhatchee
___ Clayton North
___ Clayton South
___ Cleveland
___ Clio
___ Clopton
___ Coaling
___ Coatopa
___ Coden
___ Coffee Springs
___ Coffeeville
___ Coffeeville Lock and Dam
___ Coker
___ Cold Springs
___ Columbia (GA)
___ Columbia NE (GA)
___ Columbus (GA)
___ Columbus City
___ Colvin Gap
___ Comer
___ Cooks Springs
___ Copeland
___ Cordova
___ Cottondale
___ Cottonwood
___ Courtland
___ Cox Gap
___ Coy
___ Crane Hill
___ Crawford
___ Creek Stand
___ Creel
___ Crossville
___ Crumptonia
___ Cullman
___ Cunningham
___ Cusseta
___ Cypress Inn (TN)
___ Dadeville
___ Daleville
___ Dancy
___ Danielsville
___ Danleys Crossroads
___ Danville
___ Daphne
___ Darlington (FL)
___ Davis Crossroads
___ Daviston
___ Davisville
___ Decatur
___ Delta
___ Demopolis
___ Detroit
___ Dixie
___ Dogwood Creek
___ Donalsonville West (GA)
___ Dora
___ Doran Cove
___ Dothan East
___ Dothan West
___ Double Springs
___ Douglas
___ Dozier
___ Dudleyville
___ Dugout Valley
___ Dunaway Mountain
___ Duncanville
___ Dutton
___ Dyas
___ Eastaboga
___ Echo
___ Elamville
___ Elba
___ Elkmont
___ Ellisville
___ Elrod
___ Emelle
___ Englewood
___ Enon (FL)
___ Enterprise
___ Enterprise NE
___ Epes East
___ Epes West
___ Equality
___ Estill Fork
___ Esto (FL)
___ Ethelsville
___ Eufaula North
___ Eufaula South
___ Eulaton
___ Eureka
___ Eva
___ Excel
___ Ewell
___ Falkville
___ Farley
___ Fayette
___ Fernbank
___ Fidelis (FL)
___ Fisk
___ Fitzpatrick
___ Five Points
___ Flag Mountain
___ Flat Rock
___ Flomaton
___ Florala
___ Florence
___ Flynns Lake
___ Forkland
___ Fort Benning (GA)
___ Fort Dale
___ Fort Deposit
___ Fort Gaines
___ Fort Gaines NE (GA)
___ Fort Gaines NW
___ Fort Mitchell
___ Fort Morgan
___ Fort Morgan NW
___ Fort Payne
___ Fortson (GA)
___ Fosters
___ Francis Mill
___ Frankfort
___ Franklin

Figure A-7b

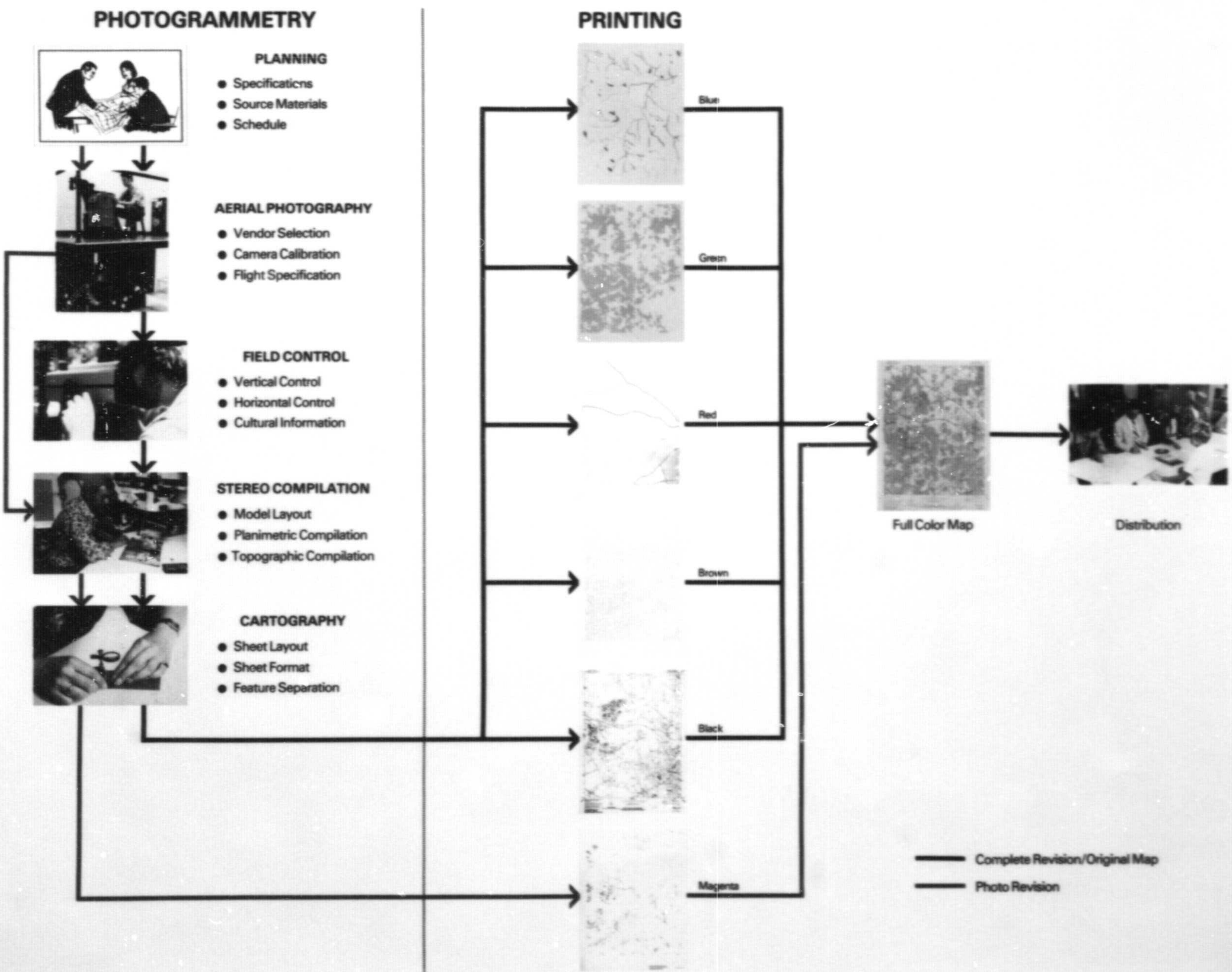
tions tested shall be in error by more than one-half the contour interval. In checking elevation, one must also be aware that the apparent verticle error may be decreased by assuming a horizontal displacement within the permissible error for a map of that scale. Stated in terms of 1:24,000 scale error on the ground, horizontal error is 40 feet and verticle error is 0.5 x (Contour interval) + 40 x (tangent of the angle of slope).

Non-quantitative errors such as map names have as yet no specifications. Allowable errors are a matter of judgement of U.S. Geological Survey staff.

Flowchart

Figure A-8 shows a flowchart that summarizes the steps in production of U.S.G.S. quads.

U.S.G.S. CHART PRODUCTION PROCESS



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ATTACHMENT I

USGS REGIONAL MAPPING CENTERS

Eastern Mapping Center
1200701 Sunrise Valley Dr.
Reston, VA 22092
(703) 860-6352

Mid-Continent Mapping Center
1400 Independence Rd.
Rolla, Missouri 65401
(314) 277-2880

Rocky Mountain Mapping Center
Denver Federal Center
Denver, Colorado 80225
(314) 234-2351

Western Mapping Center
345 Middlefield Rd.
Menlo Park, CA 94025
(303) 467-2411

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Bibliography

1. Avery, Eugene T., Interpretation of Aerial Photographs, 2nd ed. Burgess Publishing Co., 1968.

2. Bossler, John D., The New Adjustment of the North America Horizontal Datums, NOAA-NOS

3. Lippold, Admiral H.R., Readjustment of the National Geodetic Vertical Datum, American Congress on Surveying and Mapping, June 1980.

4. Manual of Photogrammetry, 4th ed., American Society of Photogrammetry, Editor Slama, Chester, C., 1980.

5. Manual of Photogrammetry, 3th ed., American Society of Photogrammetry, Editor Thomson, Morris M., 1966.

6. Manual of Remote Sensing, 2nd ed., American Society of Photogrammetry, Editor Reeves, Robert G., 1980.

7. Manual of Remote Sensing, 1st ed., American Society of Photogrammetry, Editor Reeves, Robert G., 1975.

8. Thomson, Morris M., Maps for America, USGS, 1979.

9. Topographic Maps, Periodical, USGS, 1969.

CARTOGRAPHIC MODEL

The cartographic model to be described is implemented in a computer program written in FORTRAN IV. Its purpose is to convert uncertainties in the knowlege of the sensor's postion, attitude, and scan angles into the resulting uncertainty of the ground location of an individual pixel.

Sensor location is specified by latitude, longitude, and altitude, while attitude is determined by heading, pitch, and roll angles. The line-of-sight vector from the sensor to the ground is determined by the tilt and scan angles, and the actual intersection with the ground surface is appropriately influenced by the specified terrain elevation.

Each of the above parameters and the associated uncertainties in the parameters may be altered and the consequent effects on ground location observed. In addition, the along-track and cross-track sampling intervals can be specified. These two parameters are unique in that the magnitude of the parameters, rather than the uncertainties, produce ground location uncertainties.

Execution of the program results in the presentation of a list of the default values for each parameter along with the corresponding uncertainty. Alterations are effected if desired by typing the parameter number and the new value and uncertainty.

When no more alterations are required the model is cycled twice for each parameter, once with the specified parameter and then with the parameter plus the uncertainty. The rms error attributable to each uncertainty is listed, and after all parameters have been included the rss errors for east-west, north-south, and radial directions are listed.

It should be noted that the procedure is based on the assumption that the uncertainties are uncorrelated, which is often justified in the absence of information to the contrary.

Each pass through the model begins with the calculation of earth-centered rectangular coordinates of spacecraft position and geocentric latitude from the geodetic latitude, longitude, and altitude. This is accomplished by the code in lines 101 through 108.

Next, a line-of-sight vector of length equal to the altitude and aligned with the telescope axis is created. This vector is then transformed by a single angle rotation into a coordinate space differing by a tilt angle from the telescope axis. The tilt angle permits simulation of scanners such as the Coastal Zone Color Scanner in which the scanning axis need not be aligned with the telescope axis. If the tilt angle is left at zero, the imaging model is simplified from conical scanning to planar scanning, which simulates all of the rectilinear mechanical scanners as well as electronically scanned linear arrays.

The next two transformations are through the scan angle and an assumed 45 degree orientation of the scanning flat. In this rapidly rotating coordinate system the mirror reflection is produced by negating the x coordinate, whose axis is normal to the mirror surface.

The vector is then transformed backwards through the three angles to return to spacecraft coordinates. The next three transformations are through the traditional attitude angles of roll, pitch, and heading to yield a North oriented local vertical system.

A final rotation through the geocentric latitude and the longitude angles produce coordinates for the line-of-sight vector in a system whose axes are parallel to the earth-centered system in which the spacecraft location was previously computed.

Substitution of a parametric form for the vector into the equation for the elipsoidal figure for the earth yields a quadradic easily solved for the parameter and then the intersection of the line of sight with the earth's surface. This and the conversion to latitude and longitude are accomplished in lines 131 through 139.

Any differences in the latitudes and longitudes of the intersection point for the two successive passes with and without the uncertainty present constitute the error contribution attributable to the uncertainty of the parameter. The errors are converted to meters on the surface and the root sum of squares accumulated as each parameter uncertainty is cycled in turn.

```
C
C      CARTOGRAPHIC MODEL
C
C
         IMPLICIT REAL*8 (A-H,O-Z)
       REAL*8 LT,LN,LTLP,LNLP,LTD,LND
       DATA RE,RP,DPR/6378200.,6356800.,57.2957795/
         DIMENSION P(11),DP(11),SF(11),PLT(2),PLN(2)
         REAL*8 AP(11)
       DATA REV/1.0/
         DATA AP(1)/'LAT'/
         DATA AP(2)/'LONG'/
         DATA AP(3)/'ALT'/
         DATA AP(4)/'HDG'/
         DATA AP(5)/'PITCH'/
         DATA AP(6)/'ROLL'/
         DATA AP(7)/'TILT'/
         DATA AP(8)/'SCAN'/
         DATA AP(9)/'ELEV'/
         DATA AP(10)/'ATSI'/
         DATA AP(11)/'CTSI'/
C
       WRITE (5,20) REV
20     FORMAT ('OCARTOGRAPHIC MODEL   REV '
     + ,F3.1,//)
30     FORMAT (2F10.0)
       RES=RE*RE
       EC=RE/RP
       ECS=EC*EC
         FF=45./DPR
         SDU=SQRT(1./12.)
C
C
         P(1)=0.          !LAT
         DP(1)=0.
         SF(1)=DPR
C
         P(2)=0.          !LON
         DP(2)=0.
         SF(2)=DPR
C
         P(3)=705000.     !ALT
         DP(3)=0.
         SF(3)=.001
C
         P(4)=3.14159     !HEADING
         DP(4)=.000024/DPR
```

```
              SF(4)=DPR
      C
              P(5)=0.            !PITCH
              DP(5)=.000024/DPR
              SF(5)=DPR
      C
              P(6)=0.            !ROLL
              DP(6)=.000024/DPR
              SF(6)=DPR
      C
              P(7)=0.            !TILT
              DP(7)=0.
              SF(7)=DPR
      C
              P(8)=7.5/DPR       !SCAN ANGLE
              DP(8)=0.
              SF(8)=DPR
      C
              P(9)=1000.         !TERRAIN ELEV
              DP(9)=0.
              SF(9)=.001
      C
              P(10)=10.          !ALNG TK SAMPLING INT
              DP(10)=0.
              SF(10)=1.
      C
              P(11)=10.          !CRS TK SAMPLING INT
              DP(11)=0.
              SF(11)=1.
      C
      C
              NP=11
      40      DO 50 I=1,NP
      50      WRITE(5,60) I,AP(I),P(I)*SF(I),DP(I)*SF(I)
      60      FORMAT(I3,1X,1A8,F15.4,F10.6)
              WRITE(5,70)
      70      FORMAT('$ALTER ?  ')
              READ(5,80,END=2000)I,PI,DPI
      80      FORMAT(I5,2F20.0)
              IF(I.EQ.0)GO TO 90
              P(I)=PI/SF(I)
              DP(I)=DPI/SF(I)
              GO TO 40
      C
      C
      90      SSE=0.
              SSN=0.
              SSR=0.
```

```
              WRITE(5,100)
      100     FORMAT('1PARAMETER                    EAST       NORTH
'//)
      C
      C
              DO 1000 I=1,NP
              IF(I.GT.9)GO TO 110
              IF (DP(I).EQ.0.)GO TO 1000
      C
      110     DO 200 JP=1,2
              LT=P(1)
              IF(JP.EQ.2.AND.I.EQ.1)LT=LT+DP(1)
              LN=P(2)
              IF(JP.EQ.2.AND.I.EQ.2)LN=LN+DP(2)
              ALT=P(3)
              IF(JP.EQ.2.AND.I.EQ.3)ALT=ALT+DP(3)
              HD=P(4)
              IF(JP.EQ.2.AND.I.EQ.4)HD=HD+DP(4)
              PT=P(5)
              IF(JP.EQ.2.AND.I.EQ.5)PT=PT+DP(5)
              RL=P(6)
              IF(JP.EQ.2.AND.I.EQ.6)RL=RL+DP(6)
              TILT=P(7)
              IF(JP.EQ.2.AND.I.EQ.7)TILT=TILT+DP(7)
              TH=P(8)
              IF(JP.EQ.2.AND.I.EQ.8)TH=TH+DP(8)
              EL=P(9)
              IF(JP.EQ.2.AND.I.EQ.9)EL=EL+DP(9)
              IF(JP.EQ.2.AND.I.EQ.10)PT=PT+P(10)*SDU/ALT
              IF(JP.EQ.2.AND.I.EQ.11)TH=TH+P(11)*SDU/ALT
              ALT=ALT-EL
      C
            SLT=DSIN(LT)
            CLT=DCOS(LT)
            AL=DATAN(SLT/(EC*CLT))
            RAL=RE*DCOS(AL)+ALT*CLT
            XO=RAL*DCOS(LN)
            YO=RAL*DSIN(LN)
            ZO=RP*DSIN(AL)+ALT*SLT
            GCLT=DATAN(ZO/RAL)
      C
      C
            X1=0.
            Y1=0.
              Z1=ALT
              CALL SAR(X1,Z1,TILT,X2,Z2)
              Y2=Y1
              CALL SAR(Y2,X2,-TH,Y3,X3)
```

```
                Z3=Z2
                CALL SAR(X3,Z3,FF,X4,Z4)
                Y4=Y3
                X4=-X4           !MIRROR REFLECTION
                CALL SAR(X4,Z4,-FF,X5,Z5)
                Y5=Y4
                CALL SAR(Y5,X5,TH,Y6,X6)
                Z6=Z5
                CALL SAR(X6,Z6,-TILT,X7,Z7)
                Y7=Y6
                CALL SAR(X7,Y7,-RL,X2,Y2)
                Z2=Z7
              CALL SAR (Z2,X2,PT,Z3,X3)
              CALL SAR (Y2,Z3,HD,Y4,Z4)
              CALL SAR (Z4,X3,GCLT,Z5,X5)
              CALL SAR (Y4,X5,LN,Y6,X6)
C
              AQ=X6*X6+Y6*Y6+Z5*Z5*ECS
              BQ=2.*(X6*XO+Y6*YO+Z5*ZO*ECS)/AQ
              C=RAL*RAL+ZO*ZO*ECS-RES
              T=.5*(-BQ-DSQRT(BQ*BQ-4.*C/AQ))
              XE=X6*T+XO
              YE=Y6*T+YO
              ZE=Z5*T+ZO
              PLN(JP)=DATAN2(YE,XE)
              PLN(JP)=DATAN2(YE,XE)
200             CONTINUE
C
              ELT=PLT(1)-PLT(2)
              ELN=PLN(1)-PLN(2)
              ENI=ELT*RE
              EEI=ELN*RE*DCOS(PLT(1))
                SE=EEI*EEI
                SSE=SSE+SE
                SN=ENI*ENI
                SSN=SSN+SN
                WRITE(5,210)I,AP(I),ABS(EEI),ABS(ENI)
210             FORMAT(I3,2X,1A8,6X,2F10.1)
1000            CONTINUE
C
                SSR=SSE+SSN
                SSE=DSQRT(SSE)
                SSN=DSQRT(SSN)
                SSR=DSQRT(SSR)
                WRITE(5,1010)
1010            FORMAT(//' RMS ERRORS           EAST           NORTH
RA
DIAL')
```

```
        WRITE(5,1020) SSE,SSN,SSR
 1020   FORMAT(12X,3F13.1,///)
        GO TO 40
 2000   STOP
        END
```

```
C       SINGLE ANGLE ROTATION
C
        SUBROUTINE SAR(X1,Y1,T,X2,Y2)
        IMPLICIT REAL*8 (A-H,O-Z)
        ST=DSIN(T)
        CT=DCOS(T)
        X2= CT*X1+ST*Y1
        Y2=-ST*X1+CT*Y1
        RETURN
        END
```