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Photogrammetric Methods for Mapping Resource Data from High Altitude Panoramic Photography

The generation of equal area grids, map registered grids, and polygon mapping make use of single frame resection techniques and digital terrain data.

Introduction

The U.S. Department of Agriculture (USDA) Forest Service has used conventional aerial photography to support resource management activities for over 40 years. Many of the more recent remote sensing platforms are nonphotographic sensors which operate in portions of the electromagnetic spectrum from UV through the microwave regions. These include optical-mechanical scanners for multispectral sensing thermal IR, and active and passive microwave systems. While there have been several contributions to operational programs using nonphotographic sensors, resource activities will continue to rely heavily on conventional photographic remote sensing systems for many years to come.

Abstract: *Characteristics of the Itek KA-80A optical bar panoramic camera are discussed. Two computer based mapping systems designed to correct for variations in photo scale are described. Panoramic Grid (PANGRID) is a computer program that creates a panoramic image overlay of an equal area grid assumed to lie on flat ground. The Photographic Mapping System (PMS) provides for the generation of both map registered grid overlays and mapping of digitized point, line, and polygon data. Both programs make use of single frame resection techniques and digital terrain data.*

One of the more promising systems currently under invstigation by the Forest Service is the Itek KA-80A optical bar panoramic camera. Resulting panoramic photography has shown considerable promise in supporting both large area timber salvage operations and forest insect loss assessment (Klein *et al.*, 1980; Dillman and White, 1982; and Caylor *et al.*, 1982).

KA-80A Optical Bar Panoramic Camera System Characteristics

Camera features which are particularly attractive include the ability to acquire high resolution (2 feet at nadir) stereoscopic coverage over large areas of land in a short time span. High resolution, wide angle coverage, large apertures, and low distortion were regarded as mutually incompatible objectives in camera design until the advent of the panoramic camera. A panoramic camera achieves large area coverage at high resolution by using only the center of a narrow field-of-view lens and effectively sweeping the lens across the terrain. Accordingly, lens resolution remains the same across the entire 120 degrees of scan. At the same time, large lens apertures (*f*/3.5) can provide sufficient illumination for exposure of slow speed, high resolution aerial films.

Ability to cover large areas in a short time span is a reflection of both the design characteristics of the KA-80A camera and the U-2 aircraft. Both are desireable for many resource activities. Proper timing of photographic missions is often critical because of changing targets and limited days of weather favorable for aerial photography.

The KA-80A camera produces a panoramic image on standard 5 inch wide aerial film which is 4.5 by 50.26 inches in size. Total lateral coverage is 120 degrees, 60 degrees each side of nadir. An *f*/3.5 camera lens with a local length of 24 inches

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(609.6mm), when flown at 60,000 feet above terrain, provides photography at a nadir scale of 1:30,000. Format data include time of day, frame count, lens serial number, calibrated focal length, V/H meter, stereo mode indicator light (fore/aft/vertical), center of scan marks, and 8 degree scan angle marks on both sides of the image (Figure 1). Maximum film capacity is 6500 feet of thin base film, which provides a mission data capability of 3 hours.

The KA-80A camera can be flown in a pitched fore/aft mode, providing 16 degree convergent stereo coverage. All Forest Service missions, however, have been flown in a vertical mode with 55 to 65 percent forward overlap at sea level. A single photograph flown in this configuration has a ground coverage of approximately 1.8 nautical miles at nadir and 17.1 nautical miles on either side (60 degrees) of nadir.

Forest Service flight line planning normally assumes effective film utilization out to 35 degrees of scan on each side of nadir, but specific flight line spacing is application dependent. Assuming a constant height above terrain of 60,000 feet, flight line spacing of 13.8 nautical miles will provide a useful field-of-view of 70 degrees.

The duration of a single NASA U-2C mission, from takeoff to landing, cannot exceed 6 hours. Total mission coverage obtainable can accordingly be limited by the time required to fly to and from the area of interest. Sample statistics for several Forest Service missions are summarized in Table 1.

Panoramic Geometry

The KA-80A camera system employs an optical bar principal of operation in which the entire optical system is assembled and aligned as an integral structure. The optical train is folded by means of mirrors to meet space limitations and is mounted nearly horizontally to view the terrain below the vehicle. During camera operation, the entire optical bar rotates continuously around a fore/aft axis. This causes the folded optical system to scan the terrain across the line of flight while the image of the terrain is exposed through a stationary slit onto the film. The film is simultaneously being pulled across the slit plate about the axis of lens rotation at a rate compatible with the vehicle ground speed (Figure 2). Exposure control is provided by a variable width slit plate.

There are distortions and image displacements evident on the photograph which are not present on the conventional vertical frame camera image. The most noticeable distortion is the variation in scale caused by the effective projection of the ground plane onto a cylindrical film platen. This is referred to as panoramic distortion.

Distortions of lesser magnitude are those often referred to as sweep displacement and image motion compensation (IMC) displacement. Sweep displacement is an intrack displacement resulting from the movement of the aircraft during the time the lens starts and completes its scan across the photograph. IMC displacement is introduced by an attempt to compensate for image motion during the finite exposure through the split plate. Due to the relatively high velocity of the U-2C aircraft (675 feet per second) and the high-resolving power of the optical bar camera, this motion left uncompensated can cause image smear of several resolution elements. Compensation can be provided by either moving the lens or the film or some combination thereof. The KA-80A camera rotates the lens assembly about a pitch axis in the intrack direction. The resulting IMC displacement is opposite the direction of sweep displacement. The remaining residual displacement causes parallel lines perpendicular to the direction of flight to appear as slightly distorted S-shaped curves.

The combined effect of panoramic distortion and sweep/IMC displacements can best be demonstrated by simulating the different view obtained by a framing camera when both are photographing an equal area grid on the ground (Figure 3). The cross track S-shaped distortion as shown is exaggerated for the purpose of illustration. In fact, when using only the center 70 degrees of scan, the residual displacement due to forward motion compensation ranges from zero at nadir to approximately 110 feet (34 metres) in the corner of the image at the 35 degree scan position. The corresponding displacement in the center of the image

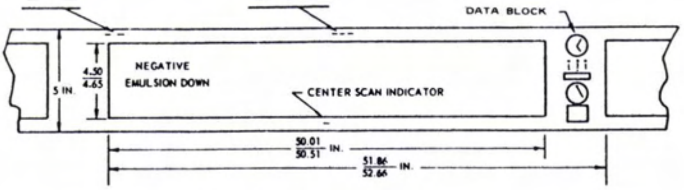


Fig. 1. KA-80A film format.

TABLE 1. TYPICAL FOREST SERVICE KA-80A MISSION COVERAGE

Area Flown	Time Over Area (Hours)	Total Useable Coverage (Plus or minus 35 degrees) Acres	Hectares
Idaho	2.8	13.2 Million	5.3 Million
California	4.5[a]	21.3 Million	8.6 Million
Colorado	1.6	7.4 Million	3.0 Million

[a] KA-80A maximum film capacity of 6500 feet provides a three-hour data collection capability. The figure shown represents two separate U-2C mission segments.

at 35 degrees of scan is approximately 16 feet (5 metres).

Figure 3 shows that, for vertical panoramic photography,

- The scale in the direction of flight is different from the scale perpendicular to the direction of flight for all points off true vertical (nadir).
- The magnitude of the intrack and crosstrack scales and the difference between them is a function of the off-nadir crosstrack viewing angle (scan angle).

The fact that scale on a panoramic photograph varies at every point together with inherent forward motion compensation distortions is, in part, what originally stimulated the need for precision analytical stereo-plotters. In most cases, conventional instrumentation built to handle frame photography cannot effectively handle panoramic photography. The few exceptions to this rule involve either small area examinations or viewing the panoramic photograph close to nadir. In both instances, panoramic geometry approaches that of frame geometry. Error is introduced, but the magnitude may be acceptable for some applications.

MAPPING TECHNIQUES INVESTIGATED AND DEVELOPED BY THE FOREST SERVICE

Distortions inherent in panoramic photography present major problems to photo interpreters, especially cartographers, because present map transfer methodologies and instrumentation are aligned towards the use of frame photography.

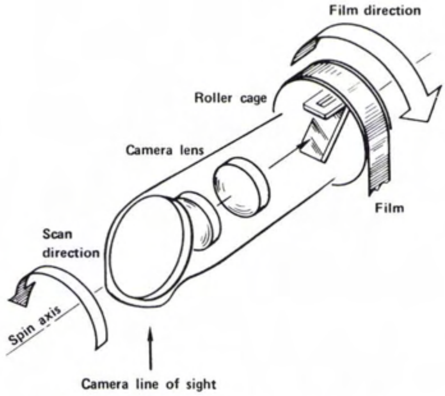
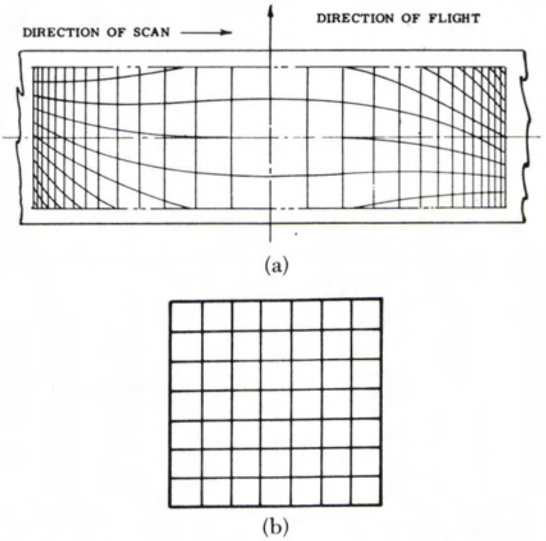


FIG. 2. The optical bar concept.

The Forest Service is involved in two types of mapping applications: resource application and engineering applications. Engineering applications are typically small area projects (i.e., timber sales) requiring precision mapping. These are supported by trained technicians operating conventional analog stereoplotting equipment. Resource applications, on the other hand, such as mapping vegetation boundaries, often cover an area the size of an entire National Forest (i.e., 1.2 million acres or larger). Mapping accuracies are less stringent and often the resource specialist does both the photointerpretation and mapping. Respective resource units are trained primarily in cartometric transfer techniques using conventional frame photography and seldom have mapping equipment, per se. Most have access to a computer and two-axis XY coordinate digitizer, however.

To date, the primary use of KA-80A photography has been in the resource application. Accordingly,



(a)

(b)

FIG. 3. Illustration of an equal area grid photographed by vertical panoramic and framing cameras. (a) Vertical panoramic photograph. (b) Vertical frame photograph.

emphasis thus far has been to identify and develop panoramic mapping techniques that can be used by the resource specialist to support large area inventories.

ANALYTICAL PLOTTERS

There is little doubt that analytical plotters are the only suitable plotting instruments for mapping from panoramic photography. They probably represent the only viable alternative for meeting the requirements of most engineering projects. The question of whether or not accuracy requirements can be achieved lies primarily with the integrity of the KA-80A photography and associated panoramic modeling. There has to date, however, been little interest shown in using KA-80A photography to support engineering project work, and the suitability issue has not yet been addressed.

The only investigation made thus far involving the use of an analytical plotter was directed towards the use of KA-80A photography in supporting 7½ minute quadrangle map revision at the Forest Service Geometronics Service Center in Salt Lake City, Utah. A single 7½ minute quad was revised using optical bar imagery and an AS-11A-1 analytical stereoplotter located at the Johnson Space Center in Houston, Texas. While acceptable map accuracy was readily obtainable, a major shortcoming was the requirement to set eight stereo models to map one quadrangle. When compared to compilation time using conventional mapping photography, use of optical bar photography in supporting map revision is not cost effective.

Based on the experience of others, together with that gained by the Forest Service in the AS-11A-1 test, there is little doubt that analytical plotters in conjunction with optical bar photography can meet resource mapping accuracy requirements. There are, however, approximately 700 field offices within the Forest Service involved in some phase of resource mapping. None currently have analytical plotters. The Forest Service currently owns two analytical plotters. Both support engineering project mapping at the Geometronics Service Center. Neither is currently equipped to handle panoramic photography. Despite the fact that there are several analytical plotters now available that cost under $100,000, this still represents a very sizeable purchase for any field office. While there will undoubtedly be field units that purchase analytical plotters in the future, the transition will be very slow, particularly with the current trend towards more stringent budgeting. In the interim, field units will have to rely on panoramic mapping techniques that can be supported with existing equipment.

OPTICAL/MECHANICAL RECTIFICATION

A rectifier was built to handle KA-80A optical bar material in support of the Apollo lunar mapping program. Its use has never been pursued seriously by the Forest Service because it was designed for rectifying high definition panchromatic 3414 emulsions. Most Forest Service applications have used Kodak high-definition aerial Ektachrome IR film (SO-131). Other factors which go against the use of a rectified product include added cost, additional delays in product delivery to the user, and increased material handling and field equipment interface problems imposed by the larger 9 by 83 inch rectified format.

CARTOMETRIC TRANSFER

The cartometric transfer of photo observables to a base map or an orthophoto quadrangle is widely used in support of some resource activities. Cartometric transfer requires local area feature matching, i.e., roads, drain lines, etc., and is of limited use in many Forest Service areas. For this reason, photo to orthophoto transfer is normally preferable, assuming the orthophoto quads are available. Currency of data, particularly in areas of high cultural change, is important in either case.

Cartometric transfer can be the lowest cost map transfer alternative when available source materials and accuracy requirements permit its application.

While there have undoubtedly been attempts by field personnel to affect cartometric transfer with KA-80A photography, results do date are not well documented. Scale variation and oblique viewing effects could prove restrictive at scan angles much above 20 degrees.

The University of Idaho, under a support contract to the Forest Service, did report acceptable transfer of transportation lines to a 7½ minute orthophoto quadrangle out to 40 degrees of scan using a Bausch & Lomb Monoscopic Zoom Transfer Scope (Befort *et al.*, 1980).

EQUAL AREA GRIDS

One can deal effectively with scale variation and sweep/IMC displacements in panoramic photography by treating scaling problems as point positioning problems. This requires the use of mathematical equations which model camera operation. The resulting equations are nearly always implemented through the use of computer programs. These programs either direct mechanical motions in a plotter (analytical plotters) or provide hard copy output in the form of maps, map overlays, or printed listings of ground coordinates.

Mathematical models and associated computer programs have been written by the Forest Service Engineering Geometronics Group in Washington, D.C., that simulate the panoramic geometry of the KA-80A optical bar camera. The projective equations required to model panoramic photography follow closely the analytics provided in the 4th edition of the *Manual of Photogrammetry*.

Using a program PANGRID (Liston, 1980), a user can effectively create an image of an equal area grid lying on the ground. The user can specify: grid cell size, grid scale, scan angle limits, and several labelling options. Image registration marks which reference 8 degree scan angle marks are also provided (Figures 4 and 5). Modeling assumptions include flat Earth approximation, vertical and stable attitude profile, and constant aircraft altitude. PANGRID output is a plot tape suitable for off-line plotting on a Calcomp drum plotter. The software resides at the USDA Fort Collins, Colorado, Computer Center (FCCC).

Both scribed and inked grid overlays have been generated. Inked overlays tend to smear with extensive handling. Accordingly, the plotted overlay is normally sent to a photographic laboratory for reproduction on film. Scribed plots (2 to 3 mils) produce a useable product when the panoramic image and attached overlay are viewed under 8 or 16× magnification.

The equal area grid overlay has proven to be a useful photointerpretation aid. The approximate size of small features can be estimated in proportion to the nearest grid interval. Longer distances can be determined by counting the number of grid intervals included. This may require proportional estimating of partial grid intervals at either end. Counting grid cells provides a relatively quick and accurate means of determining areas. The nature of the grid itself supports the systematic recording and extraction of photo observables on a cell by cell basis over a large project area, i.e., the number of dead/dying trees per cell.

The grid can also be used to provide a relatively quick means of base map transfer as demonstrated in a feasibility pilot test to map dead timber on the Clearwater National Forest in Idaho (Weber *et al.*, 1977). Manual transfer requires the use of an additional equal area grid drafted at base map scale. Cell registration is provided by identifying at least two points separated by approximately 20 degrees of scan, which are common to both the base map and photo overlay. The equal area base map grid can then be manually oriented to coincide with the grid overlay. A cell numbering system common to both the base map and photo grid provides for less confusion in the map transfer process.

A minor modification of the manual approach could provide for the automatic plotting of cell observables on the base map. This could be particularly applicable if cell observables have already been entered into a digital data base. This requires recovering the *XY* coordinates of the same two registration points on both the grid overlay and the base map. A simple two dimensional translation and rotation provides for the transformation of grid cell data to the respective base map.

Equal area grids have proven to be attractive to Forest Service users of optical bar photography

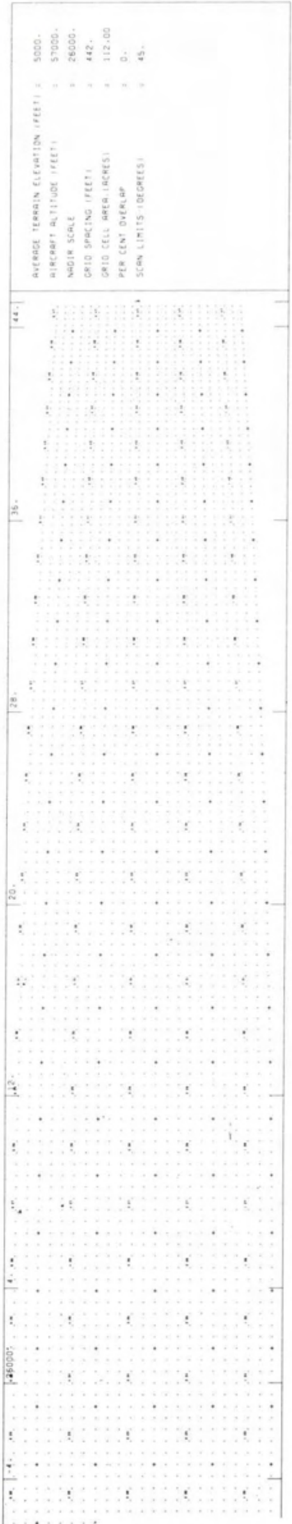
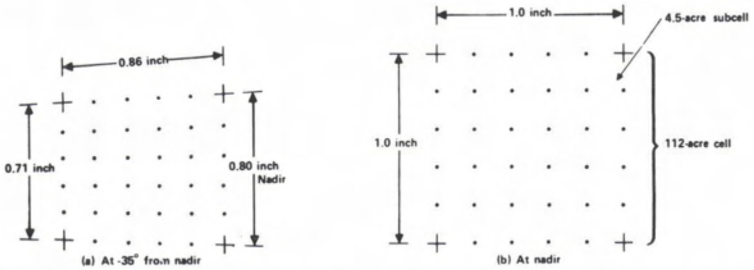


FIG. 4. A KA-80A equal area grid.



(a) At -35° from nadir

(b) At nadir

FIG. 5. Equal area grid cells at nadir and at −35 degrees from nadir (nadir scale = 1:26,000).

primarily because field interpreters have been using grids on conventional frame photography for years and they understand how to use them and know their limitations, they are easy to generate, they are easy to use, they support many mensuration needs utilizing existing viewing equipment, when taped to the image they can be taken into the field, and last but not least, multiple copies on paper or film base material can be provided at low cost, i.e., $2.00 per copy.

The principal disadvantage of equal area panoramic grids is that, when used to position cell information on a base map, very sizeable transfer errors can result at higher scan angles due to departures from the flat earth approximation used in grid generation. Positional errors (Pe) likely to occur can be approximated by the relationship

$$Pe = \text{Tan (Scan Angle)} \times (Em\text{-}Eh)$$

where

Em = map elevation and

Eh = average terrain elevation used in grid generation.

Positive differences move the cell position away from nadir. Negative differences move the cell toward nadir.

Another problem which has been encountered in large area surveys is the grid cell overlap or data gap which occurs at the cross track boundary between two adjacent overlays, i.e., every other photograph within a flight line. Either can occur whenever grid cell intervals are not an equal increment of the projected frame intrack ground distance less overlap distance. Factors contributing include inherent topographic distortion, differential crabbing of the aircraft during acquisition, the grid cell size used in grid generation is too large or too small, and improper setting of frame overlap for the mission, i.e., percent overlap is specified at mean sea level instead of mean datum. While the occurrence of data gaps and overlap can be minimized, a user cannot expect that they will be completely eliminated. This is particularly true in mountainous country.

MAP REGISTERED EQUAL AREA GRID CELL OVERLAYS

Most lands administered by the Forest Service, particularly in the West, occur in mountainous terrain. In light of the aforementioned attractiveness of grid overlays, a logical next step was the development of a grid generation capability that would compensate for both terrain elevation differences and errors in aircraft attitude, i.e., map registered grids.

A software based system was developed, the Photographic Mapping System (PMS), which will generate map-registered grids for either KA-80A panoramic photography or instantaneous frame photography (Liston, 1979). Single frame resection analytics provide for recovery of aircraft position and attitude. The USGS National Cartographic Information Center (NCIC) digital terrain data formerly generated from the Defense Mapping Agency (DMA) 1:250,000 series mapping program, provides for elevation compensation.

A user must have access to a two-axis XY coordinate digitizer which preferably has both back lighting and a least count of 1 mil. Procedures involved in grid generation include

- Ordering NCIC digital terrain data;
- Creating, testing, and merging disk resident terrain files;
- Identifying, marking, and measuring XY coordinates of three to six control points on each photograph and its associated 7½ minute quadrangle map; and
- Executing three computer programs which provide for the generation of UTM coordinates of map control points, recovery of aircraft attitude and position, and generation of a map registered grid plot tape.

PMS initially resided on a SEL 32/55 minicomputer located at the USGS Eastern Mapping Center in Reston, Virginia. It is presently operational on the USDA computer facility in Fort Collins, Colorado.

The SEL based system has been used to support several small area demonstration projects. Map registered grids have been generated for both the Itek KA-80A optical bar panoramic camera and the

Hycon HR 732 9 by 18 inch large-format framing camera. Several pallet configurations are routinely flown by the NASA Ames Research Center U-2C incorporating either camera type.

Experience has shown that grid cell location accuracies of 200 feet (61 metres) or better are readily obtainable when using the central 90 degrees of scan. The primary limitation is the inherent 150 to 200 foot (46 to 61 metres) accuracy in the NCIC DMA digital terrain data. Map registered grid generation costs are high, averaging $50.00 per grid cell overlay. Sixty percent of the cost is in the labor required to support photo indexing, control point selection, marking and measurement, and data preparation for running computer programs. Accordingly, the FCCC operational system will make use of *N* photo block logic, enabling the bridging of up to 100 optical bar photographs, i.e., a 100 mile flight line. It is expected that bridging will significantly reduce the overhead costs associated with control point recovery, photo indexing, and data preparation. Simulations have been made by generating equivalent frame coordinates for panoramic photography and processing them through a conventional *N* photo block model. Results indicate that grid generation costs of $25.00 per overlay may be obtainable.

The map registered grid retains all of the advantages of the equal area grid, except cost and ease of generation. They provide positional transfer accuracies in mountainous terrain that are acceptable for a number of resource applications. Automatic or manual plotting of grid cell observables on to a base map is straightforward and simple. Grid cell overlaps or data gaps between adjacent intrack grid overlays, which present a problem when using the equal area grid, are for the most part eliminated.

Grid generation requires high-level skills in both data processing and photogrammetry. Therefore, a resource photo interpreter will most likely have to rely on grid generation by skilled personnel at a Regional Geometronics Office or Geometronics Service Center.

MAPPING POINT, LINE, AND POLYGON DATA

A user may find that drawing polygons directly on the panoramic photograph or an overlay defines the photo observable more accurately than classification of grid cells.

The PMS system also provides the ability to map and label digitized points, lines, and polygons delineated on a panoramic photograph.

Modeling is, to a certain point, identical to that required for generating map registered grid overlays. The projective transformation required is the inverse, being photo to map instead of map to photo. Single frame resection and the use of digital terrain data are common to both. Capability is provided for merging single frame data sets together to provide a continuous data set over a 7½ minute quadrangle. Polygon data can be output in a standard data exchange format for input to the Resource Information Display System (RIDS), a Forest Service overlay processing system operational at the USDA Computer Center in Fort Collins, Colorado (Pelletier, 1979).

Polygon mapping from optical bar photographs is in a preliminary stage of test and evaluation. Testing, thus far, has been confined to software development. Map-positional accuracies similar to those pertaining to map-registrated grids, i.e., 200 feet (61 metres) or better, have been obtained.

CONCLUSION

The unconventional format of panoramic photography has posed problems in both viewing and mapping. Mapping techniques must be confined to those that can be implemented with existing equipment and personnel. The techniques developed to date, for the most part, reflect these constraints. Equal area grid generation requires access to a large mainframe computer and an off-line plotter. Similarily, map registered grid generation and polygon mapping under the PMS system will require access to a mainframe computer, an off-line plotter, and a two-axis coordinate digitizer. While the PMS system does require a higher level of skill to use, these skills can be provided through appropriate training of Regional personnel.

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